ABSTRACT

Fei-Wen Deng The Influence of Adding Alum on Biological Phosphorus Removal and Nitrification in Sequencing Batch Reactors.

(Under the direction of Dr. James C. Lamb).

One of the approach for improving reliability of biological phosphorus removal could be adding alum to activated sludge mixed liquor. Other studies of limited scope had suggested that such additions might adversely affect nitrification in the treatment system. In many plants that must meet a stringent effluent ammonia limit, that situation could cause serious problems in meeting permit requirements.

A bench-scale sequencing batch reactor (SBR) experiment was conducted, using a control unit without alum addition and three units that received different dosages of alum. The results showed that: 1) Adding alum seems have no adverse effect on biological phosphorus removal, 2) the addition of alum may exert adverse effects on nitrification, and 3) acetate plays an important role in biological phosphorus removal.

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CONTENTS

List of Tables

List of Figures

INTRODUCTION

The eutrophication of lakes and rivers is a serious problem in many of our natural waters. Phosphorus is one of the nutrients that often can limit development of eutrophic conditions and, therefore, the amount of phosphorus that can be discharged in wastewater discharges has been limited by regulatory agencies in many areas.

There are two broad categories of phosphorus removal processes. The first is chemical precipitation using alum, iron salts or lime. Its main disadvantage is the cost for chemicals and sludge handling. Another approach is biological phosphorus removal (BPR) in an activated sludge process. This has the potential for better cost-benefit relationships than chemical precipitation processes. However, BPR may not be operated as easily as chemical precipitation for reliable phosphorus removal because the mechanisms of BPR are still not well understood, and design and operating standards are less well developed.

One approach to assure meeting the limits for effluent phosphorus concentration is to add chemicals after the BPR system as post-treatment to compensate for uncertainty of BPR processes. This would require construction and operation of an additional set of final clarifiers.

Although combined chemical-biological treatment which removes phosphorus by adding alum to activated sludge aeration tanks was investigated and proved feasible in the 1970's, those studies included only consideration of conventional activated sludge processes. If BPR is possible simultaneously with alum addition, the result might be both economical and reliable. It is not clear, however, whether the combined treatment would adversely affect BPR performance or nitrification. Therefore, it was decided to investigate the impact of adding chemicals to mixed liquor in BPR systems.

Among the processes modified for BPR, sequencing batch reactors (SBR) are felt by some to be highly promising (Manning, 1985). The SBR is a recently developed technology, based on the fill-and-draw activated sludge process. A full-scale plant at Culver, Indiana, has produced consistent biological removal of phosphorus. This study used the SBR process because of its potential for BPR and the simplicity of such an installation.

OBJECTIVES

The objective of this report are to;

1) review the theories of phosphorus removal in activated sludge processes;

2) review the technology of sequencing batch reactors;

3) investigate the effects on BPR of adding alum to bench scale sequencing batch reactors; and

4) investigate the effects on nitrification of adding alum to bench scale sequencing batch reactors.

LITERATURE REVIEW

Theories of Phosphorus Removal in Activated Sludge

Details of actual mechanisms involved in phosphorus removal during activated sludge processes are still largely unresolved. In general, phosphorus removal mechanisms have been explained mainly in terms of : (1) normal cell requirements; (2) luxury uptake; and (3) chemical precipitation.

(1) Normal Cell Requirement

Bacteria utilize phosphorus as part of their metabolic processes in synthesizing microbial material, for which a composition of $C_{106}\ H_{180}\ O_{45}\ N_{15}\ P$ is often cited (Lan et al.,1983). From analyses of sludges, 2-3% of phosphorus on a dry-weight basis often is reported. Usually 20 - 30 % of the influent phosphorus may be removed by microbial growth in municipal treatment systems. This is based on the stoichiometric composition of the microorganisms and the amounts of cell material generated in biological processes.

(2) Luxury Uptake

Some investigators have reported that biological storage, or luxury uptake, is responsible for any further phosphorus removal beyond normal microbial growth requirements. The

mechanism can be discussed from two major aspects of biochemistry and microbiology.

a) Biochemistry

Basically, luxury uptake can occur when the organisms are subjected to a sequence of anaerobic-aerobic conditions. During the anaerobic phase, certain phosphorus-accumulating organisms hydrolyze stored polyphosphate (poly-P) to simple orthophosphate (ortho-P) to obtain energy for the uptake of organic substrates. Upon entering the aerobic stage, the remaining substrates are oxidized, and some of the energy derived from them is used to form poly-P and cell material. This results in low concentrations of both phosphorus and organic substrate in the liquid.

Barth and Stensel (1981) point out that the biological phosphorus removal capability for a given system is a function of the influent biochemical oxygen demand (BOD) and phosphorus concentrations, sludge residence time (SRT), and phosphorus percentage in the sludge. Marais (1983) proposes a population selection theory that under anaerobic/aerobic conditions, poly-P accumulating organisms gain an advantage over non-poly-P accumulating organisms. Fukase, Shibata, and Miyaji (1984), however, do not agree that poly-P must be present in phosphorus-removing organisms. They point out

that microorganisms containing poly-P appear to have no advantage over others in adsorbing BOD under anaerobic conditions. They conclude that not only the addition of an anaerobic stage in the activated sludge process, but also the influent BOD concentration is important in enhancing phosphorus removal. Manning and Irvine (1985) suggest that an anaerobic period with excess substrate allows phosphorus-accumulating organisms to compete favorably, and the aerobic period which follows is essential to the final enrichment of the organisms.

Florentz et al. (1984) have found that nitrates can affect phosphorus assimilation by inhibiting release of phosphorus to the liquid although they found no disturbing effect on phosphorus assimilation inside the cell. Hascoet and Florentz (1985) point out that the permissible nitrate in return sludge depends on the influent chemical oxygen demand (COD). If the influent COD is sufficiently high, the recycled nitrates have a negligible effect on the phosphorus removal process.

Marasis, Loewanthal, and Seibrite (1983) report that the ability to form poly-hydroxy butyrate (PHB) is important to the phosphorus removing organisms. They suggest that PHB is involved in the supply of ATP, reducing energy and carbon source for a variety of synthetic pathways, especially under

aerobic conditions. Potgieter and Evens (1984) also propose that luxury uptake of phosphate is the result of microbes existing under partial stress. Partial stress is caused by an imbalance in the biochemical energy pool (in the form of ATP and reduced cofactors), carbon source, and other components such as sulfide and ammonia.

In order to find the pathways of luxury uptake, Florentz et al.(1984) used ^{31}P nuclear magnetic resonance (NMR) to observe the displacement of stored phosphorus from the poly-P form to soluble phosphorus (Pi) form during the non-aerated period. They state that this displacement is very rapid in the presence of carbonaceous pollution and is slow in its absence. The transfer process reverses immediately upon aeration. Their works are in agreement with the biochemical model proposed by Marais and co-workers (1983) who propose the following equation :

2 acetate + 2 ATP = acetoacetate + 2 ADP + 2 Pi

When the pollutant is degraded and stored in the organisms in the form of acetoacetate, two molecules of Pi are released. An osmotic pressure is created as the stored polyphosphate decreases and the phosphorus in the cell increases. Thereby, the phosphorus diffuses through the cytoplasmic membrane and increases the phosphorus concentration in the bulk liquid.

b) Microbiology

Fuhs and Chen (1975), and Buchan (1983) report that Acinetobacter spp can store phosphorus in metachromic volutin granules and mainly use acetic acid as substrate. Nicholls and Osborn (1978) find good correlation between the removal of phosphorus in an activated sludge plant and the presence of the volutin granules in the organisms. They also state that not only Acinetobacter are responsible for the accumulation, but other facultative bacteria are also capable of phosphorus removal. Brodich and Joyner (1983) propose that Aeromonas and Pseudomonas may also contribute to biological phosphorus removal. Florentz and Hartemann (1984) further identify that Bacillus cereus and Pseudomonas cepacia individually accumulate more phosphate during the stationary phase than Acinetobactor in a meat extract medium without acetate. However, they point out that supplying acetate to a pure culture of Acinetobacter entails a significant over-accumulation of phosphorus which is stored in the form of poly-P granules inside the cellular cytoplasm. Lotter (1985) suggests that the short-chain carbon compounds, such as acetate and butyrate, can stimulate phosphorus accumulation.

After comparing various short-chain carbon compounds, Gerber et al.(1986) report that the most favorable compounds for stimulating phosphorus removal are acetate, butyrate,

propionate, and lactate. Chiesa and Bordacs (1986) suggest that intermittent-carbon-supplementation can be used to improve long-term BPR efficiency and reliability. The frequency and magnitude of supplemental carbon addition depends on the organic loading history of the system.

(3) Chemical Precipitation

As mentioned before, not all researchers agree that enhancedphosphorus removal is the result of biological mechanisms. Some believe that the improved phosphorus removal results from physical-chemical phenomena.

Menar and Jenkins (1969) hypothesized that calcium phosphate precipitation followed by sorption accounts for exceedingly high phosphorus removal. They state that the formation of a calcium phosphate sludge is induced by higher pH, which is caused by decreased production and increased stripping of carbon dioxide during the aeration period. Riding et al.(1979) also observed that much higher phosphorus removal can occur in wastewater which contains high concentrations of calcium ion. However, Milamoto-Mills et al. (1983), and Gerber and Winter (1984) find no significant variation in calcium concentration when the wastewater passes through anaerobic,anoxic, and aerobic process stages. Walsh et al.(1983) believe the change in oxidation-reduction

potential (ORP) between anaerobic and aerobic phases contributes to phosphorus removal. They report that calcium, magnesium and iron (potentially contained in the enzyme layer on the exterior of cells) solubilize during the anaerobic phase because of the low ORP; these reactions cause the phosphorus release. During the aerobic phase, these ions precipitate inorganic phosphorus because of the high ORP.

Other researchers contend that both biological and chemical precipitation mechanisms are involved in phosphorus removal, especially when removals below 1 mg/l are obtained (Barnard, 1983; Lan, et al., 1983; Fukase,et al., 1984). However, Lan et al. point out that for systems operating at high pH (pH>8), the precipitation of phosphorus by calcium or other metals can represent the most important mechanism. Arvin (1983) proposes that under anaerobic conditions, biological phosphorus release can initiate and accelerate phosphate precipitation. Therefore, chemical precipitation of phosphorus in wastewater is improved by the BPR process.

Technology of Sequencing Batch Reactor (SBR)

(1) Description of System

TheSBR is a fill-and-draw activated sludge system,which may be composed of two or more tanks to accommodate a continuous inflow of wastewater. Five discrete operating periods occur for each cycle - FILL, REACT, SETTLE, DRAW, and IDLE.

FILL is the period of receiving raw waste with mixing and/or aeration to provide distinct, selective growth conditions for microbial biomass (Manning,1985). The REACT period follows and completes desired reactions by holding and aerating contents of the full tank. SETTLE is the period in which the biomass is allowed to flocculate and settle under quiescent conditions for a predetermined time. This is followed by the DRAW period, in which the treated effluent is decanted to the design minimum liquid volume level. The IDLE period is used for awaiting resumption of the influent wastewater flow to refill the tank and start another cycle.

(2) Historical Perspective

SBR is the precursor to modern day continuous flow activated sludge technology. In 1914, Ardern and Lockett were among the first to show the benefit of retaining

substrate-adapted organisms for efficient treatment. However, this early fill-and-draw activated sludge system was never applied to any great extent because of the lack of suitable aeration equipment to prevent plugging with stop-start operation, the unavailability of automatic valving, timing, and switching technology and equipment, and the lack of understanding of the biokinetic advantages of batch systems (Mandt, 1985).

Now new hardware devices, such as motorized valves, pneumatically actuated valves, solenoid valves, flowmeters, level sensors, automatic timers, and process controllers or microprocessors,have been developed and are available (Arora et al., 1985). These improvements provide the capability for SBR technology to reach its full potential. EPA has been re-evaluating SBR technology since the early 1980s. During the past decade, researchers at the University of Notre Dame have demonstrated the strong potential of SBR for energy savings and reliable operation. Nevertheless, the lack of widely accepted design standards has delayed application of SBR technology. A full scale demonstration plant at Culver, Indiana, has been funded and the results of that project may facilitate the use of SBR's at other municipal facilities.

(3) COMPARISON OF SBR AND CONTINUOUS FLOW PROCESSES

Conceptually, SBR involves timed unit processes which all occur sequentially within the same vessel. A continuous flow system involves spacially related unit processes. Mandt (1985) compared SBR and continuous flow parameters in a way similar to Table 1.

(4) Advantages of SBR

Based on the evaluations by Arora et al.(1985) and Mandt (1985), the advantages of SBR are:

a) Flow equalization is inherent, therefore, SBR can control flows and organic shock loads within the constraints of reactor volume and oxygen supply.

b) The phases of SBR can be modified, within limits, to attain the desired effluent quality.

c) No return sludge pumping and secondary clarifiers are required.

d) Solid-liquid separation occurs under nearly ideal quiescent conditions.

e) During the initial REACT period the oxygen utilization capacity of organisms will generally exceed the transfer capabilities of the aeration system. Thus higher overall

Table 1. COMPARISON OF SBR AND CONTINUOUS FLOW PROCESSES

PARAMETER	SBR	CONTINUOUS
Concept	Time Sequence	Spatial Sequence
Inflow	Periodic	Continuous
Discharge	Periodic	Continuous
Organic Load	Cyclic	Even (by convention)
Hydraulic Load	Cyclic	Even (by convention)
Aeration	Intermittent	Continuous
Mixed Liquor	Always in Reactor, No Recycle	Recycles Through Reactor and Clarifier
Clarification	Quiescent Settling	Continuous Flow
Flow Pattern	Perfect Plug	Complete Mix or Approaching Plug
Equalization	Inherent	None
Flexibility	Considerable	Limited

Source : Mandt (1985)

oxygen transfer efficiency can be achieved by the greater driving gradient from an anoxic FILL to an aerobic REACT period.

f) Filamentous growth can be easily controlled by varying the operating strategies during FILL. Floc forming organisms are more capable of storing substrate during anoxic periods than filamentous organisms.

g) SBR can be operated to achieve phosphorus removal, nitrification, or denitrification.

(5) Biological Phosphorus Removal in SBR

As suggested by Manning and Irvine (1985), the flexibility of SBR seems ideally suitable for biological phosphorus removal. They state that phosphorus release is hastened by the presence of soluble COD during anaerobic periods but also depends on the prior removal of oxidized nitrogen from the system. They also observe that the mode of operation can greatly affect sludge settling characteristics; however, excellent biological phosphorus removal can be obtained during periods of high sludge volume index (SVI>500 ml/g).

Ketchum, et al. (1987) conclude that the SBR operating mode provides a proper balance of anoxic, anaerobic, and

aerobic conditions for biological phosphorus removal without any chemical addition. They propose that four major groups of organisms are involved in the SBR biological phosphorus removal: denitrifying organisms, fermentation product-manufacturing organisms, phosphorus-accumulating organisms, and aerobic heterotrophs and autotrophs.

Anaerobic conditions favor the fermentation product-manufacturing organisms to use organics in the incoming wastewater and produce by-products such as biodegradable acetic acid. Meanwhile, phosphorus-accumulating organisms release stored poly-P to provide energy for accumulating these by-products. The subsequent aerobic conditions allow phosphorus-accumulating organisms to use storage products for growth and providing energy to take up the phosphorus in solution as intracellular poly-P. Further treatment is achieved by aerobic autotrophs and heterotrophs using residual substrate. In the next FILL cycle, these organisms are prepared to release poly-P and store by-products during anaerobic conditions.

EXPERIMENTAL DESIGN

Design Criteria

Since there are no widely known standards for SBR design, the SBR design in this study was based on other SBR studies, which were not shown here, and the suggestions given by Arora et al. (1985). In this study, four reactors were operated parallel and an 8-hour operating cycle was used, with a 3-hour FILL period (anaerobic phase), 4.25-hour REACT period (aerobic phase), 0.5-hour SETTLE period, and 0.25-hour DRAW/IDLE period.

During the FILL period, wastewater, sodium acetate,and nitrogen gas were fed continuously into the reactors, and mixers were used to provide adequate mixing. Nitrogen gas was provided to hasten and insure anaerobic environment for denitrification and phosphorus release. The sodium acetate was added as substrate according to suggestions by Manning (1985), Lotter (1985), and Gerber (1986). At the end of the FILL period, wastewater, sodium acetate, and nitrogen gas were stopped and air was provided for the REACT period. Nitrification and phosphorus uptake happened during the REACT period, and mixed liquors were wasted near the end of this period. The volume of wasted mixed liquor is equal to the total volume of mixed liquor (18 liters) divided by mean cell residence time (MCRT).

During the last five minutes of REACT period, different dosages of alum were added to three of the reactors while no alum was added to the control unit, representing a BPR activated sludge system. After the five minutes, the alum feed, air, and mixer were stopped for SETTLE period. After SETTLE period, each reactor drained out one half of the total volume of mixed liquor as effluent (9 liters). The SBR design criteria are given in Table 2.

Table 2. SBR Design Criteria

Parameter	Magnitude
Cycle Time	8 hour
Cycles in Each Reactor	3 cycle/day
FILL Period	3 hour
Volume of Primary Effluent Feed	9 L
Nitrogen Gas Flow Rate	50 ml/min
REACT Period	
Total Volume of Mixed Liquor	18 L
Air Flow Rate	2450 ml/min
SETTLE Period	0.5 hour
DRAW Period	0.25 hour
Volume of Effluent	9 L
Mean Cell Residence Time	12 day
Volume of Wasted Mixed Liquor	1.5 L/day

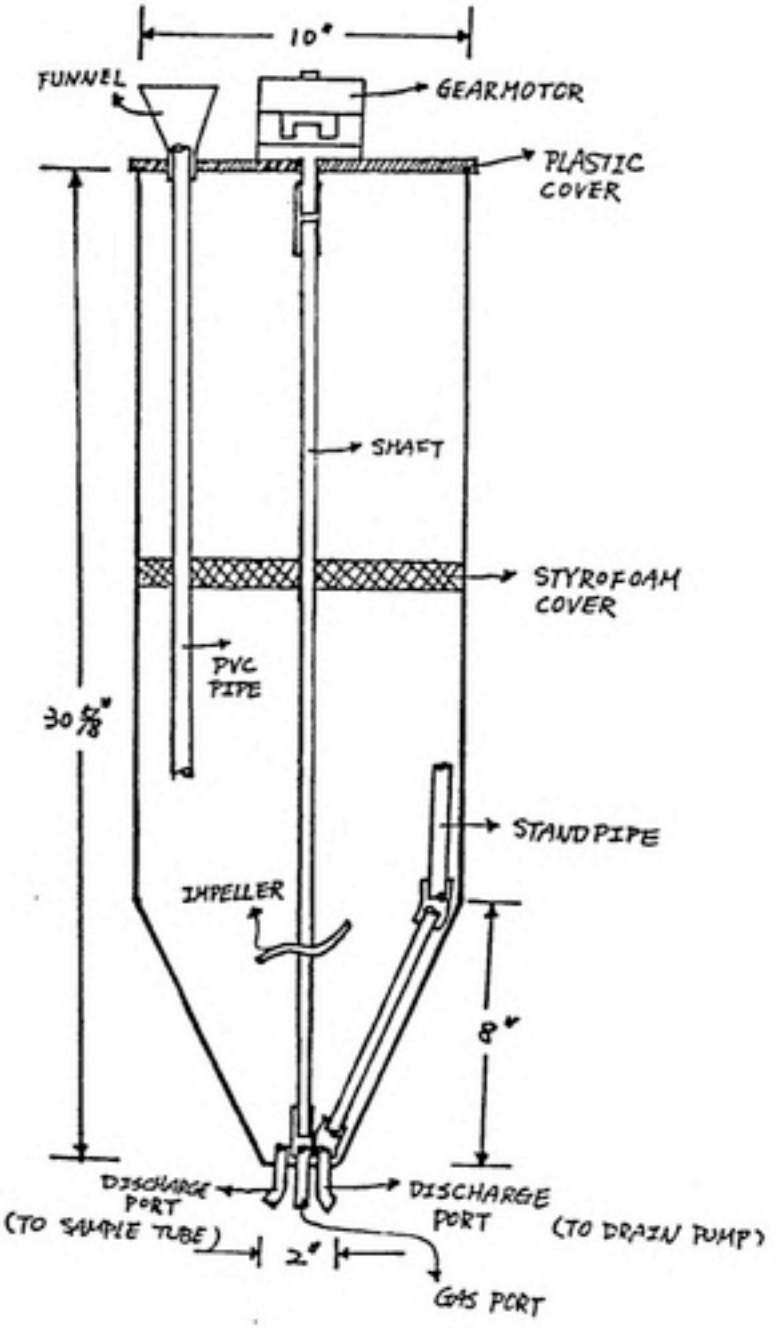
Apparatus

Four 33.7 liter (total volume) stainless steel cylindrical tanks, as shown in Figure 1, were used for the reactors. Each tank was 10 inches in diameter and 30 5/8 inches high. The bottom 8 inches were sloped at 2:1 to form a cone which helped prevent sludge accumulation.

(1) Feed

Effluent from the primary clarifier of the Mason Farm Wastewater Treatment Plant at Chapel Hill was pumped into the laboratory continuously. This was the wastewater influent to the laboratory SBR systems. The actuation of all feed pumps (influent, acetate, and alum) was controlled by a timer. A TECHNICON proportioning pump was used to feed sodium acetate at a low flow rate (0.32 ml/min). MASTERFLEX pump heads, variable speed drives, and solid state speed controllers were used for the influent and alum feed flows. MASTERFLEX tubing was used in the pump heads and TYGON tubing was used for all other liquid and gas lines. All feeds were added through funnels fixed on top of the reactors; PVC pipes extended into the tanks to prevent the splashing of feed causing air transfer during anaerobic phase.

FIGURE 1. DIAGRAM OF SBR REACTOR



(2) Gas

The conical bottoms of each tank contained three outlets, one of them was used as a gas port which was connected to a gas line receiving either air or nitrogen gas. The gases were filtered by GILMONT No. 12122 0.2 um autoclavable mini capsule filters. The flow rates of nitrogen gas were measured with GILMONT No.11 compact flowmeters and air flows were measured with MANOSTAT 36-546-215 flowmeters. The air and nitrogen flows were turned on or off by DAYTON 6X543 solenoid valves actuated by timers. Styrofoam covers were used on the liquid surface in each reactor to reduce oxygen transfer from the atmosphere.

(3) Mixing

Shafts and impellers, connected to DAYTON 200 rpm gearmotors, were used to provide mixing during anaerobic and aerobic phases. Nitrogen gas and air also provided additional mixing during anaerobic and aerobic phases, respectively. All the mixing was turned off by a timer-actuated relay during SETTLE and DRAW periods.

(4) Discharge

The other two holes on the bottom of each cone were used as discharge ports. One was connected to the sample tube and

the other was connected to the drain pump from the standpipe. The samples were withdrawn manually while drain pumps were controlled by timers. The volume of effluent from each tank, controlled by a standpipe in the reactor, was designed to be 9 liters out of 18 liters total liquid volume. Note that the IDLE period was included in the DRAW period, which is 15 minutes, in this experiment. The system flow schematic is illustrated in Figure 2.

(5) Timer control

A DAYTON 2E026 24-hour program time switch was used as the main timer to control the 8 hour repeating cycle, with 3 hours normally closed (N.C.) for the FILL period and 5 hours normally open (N.O.) for the rest of the cycle, as shown in Figure 3. Cycles started at 8:00 AM, 4:00 PM, and 12:00 midnight.

During the 3 hour FILL (anaerobic) period, the influent and acetate pumps were actuated by the normally closed circuit. The normally-closed solenoid valve connected to the nitrogen gas tank was actuated to open. Meanwhile, the motor mixers and the second normally-closed solenoid air valve controlled by a relay were actuated through the separate normally-closed relay. Since the first normally-closed solenoid air valve connected to the air source was not actuated, no air was provided during this period.

FIGURE 2. SYSTEM FLOW SCHEMATIC

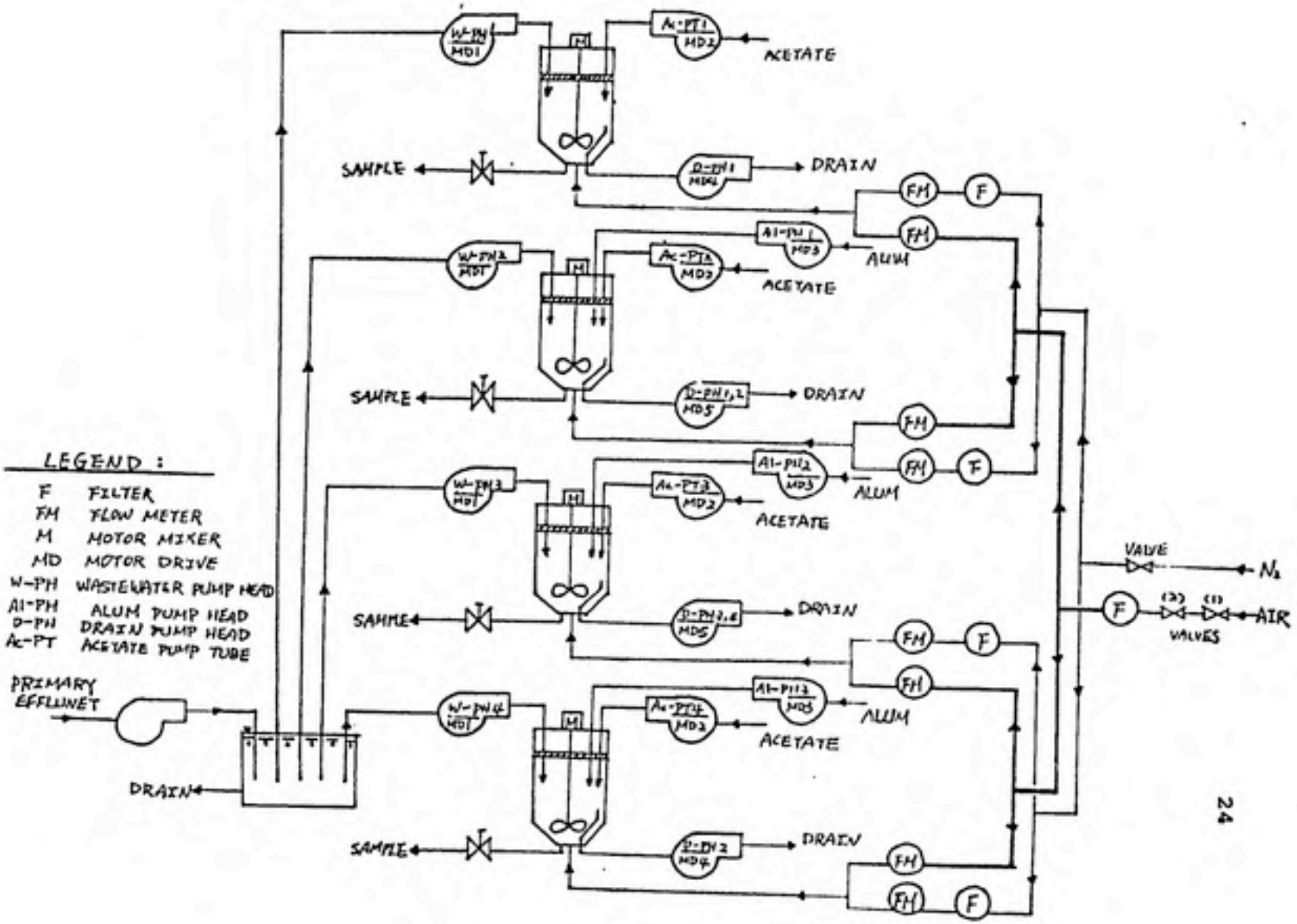
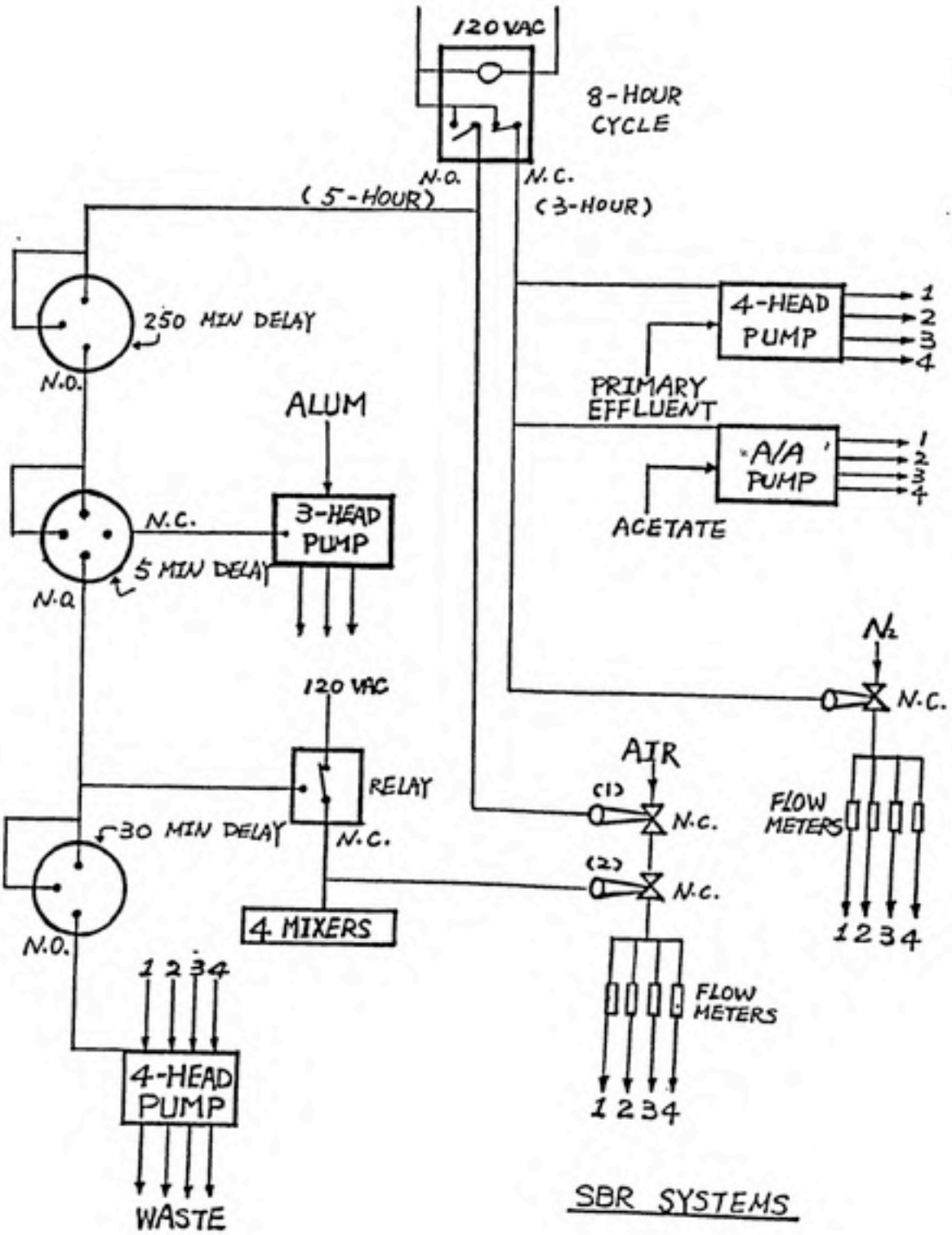


FIGURE 3. SBR TIMER CONTROL DESIGN



After 3 hours, the normally closed circuit of the main timer switched off and the normally open circuit was actuated, terminating the influent, acetate, and nitrogen gas feeds. Meanwhile, a 5 hour delay timer, set at 250 minutes, was actuated, and the first air valve was opened for the REACT (aerobic) period. After 250 minutes, the normally-open contacts of the delay timer closed and the alum feed pump was activated through the normally-closed contacts of a 15 minutes timer, set at 5 minutes. After 5 more minutes, the alum pump stopped and a 30 minute delay timer, set at 30 minutes, was actuated for the SETTLE period. At the same time, the 120 VAC relay was switched to open, stopping the mixers and closing the second air valve. After 30 minutes, the drain pumps were actuated by the 30 minute timer for the DRAW period to drain treated effluent. At the end of 15 minutes, DRAW period, another entire cycle was started by activating (closing) the normally closed circuit on the main time switch. The status of pumps, valves, and mixers during each SBR period are illustrated in Table 3.

All timers described above are CRAMER 472A-E reset timers wired to reset upon opening switch supplying power to the timer. These timers all reset upon opening of the normally open circuit of the 24 hour main time switch. A SOLA 1200-A standby power source was provided to prevent undesired timer resets from a temporary power interruptions.

Table 3. APPARATUS STATUS DURING SBR PERIODS

	FILL	REACT	(ALUM) (FEED)	SETTLE	DRAW
Duration (hour)	3.00	4.25	(5 mins)	0.50	0.25
Influent pump	ON	OFF	OFF	OFF	OFF
Acetate pump	ON	OFF	OFF	OFF	OFF
Nitrogen valve	ON	OFF	OFF	OFF	OFF
Air valve 1	OFF	ON	ON	ON	ON
Air valve 2	ON	ON	ON	OFF	OFF
Alum pump	OFF	OFF	ON	OFF	OFF
Mixer	ON	ON	ON	OFF	OFF
Drain pump	OFF	OFF	OFF	OFF	ON

Experimental Stages

This study was divided into four experimental stages to investigate the effects of alum additions under different conditions.

(1) Start up

Initially, each reactor was filled with nine liters of mixed liquor. Five of nine liters were collected from the Mason Farm Plant's aeration basin and the other four liters were from other pilot units that were successfully removing phosphorus biologically. The reactors were started in the anaerobic phase. A performance testing stage was used to test the similarity between reactors under the same operating conditions. No alum was added until similar results were reached in these four reactors. The data for this stage is given in Appendix A-1. After the performance testing stage, reactor #1 was chosen as the control unit, which received no alum additions. Reactors #2, #3, and #4 received 26, 52, and 104 mg/l of alum ($Al_2(SO_4)_3 \cdot 14H2O$), respectively. These doses would have been enough to precipitate 2, 4, and 8 mg/l of dissolved phosphorus (based on an Al:P weight ratio of 1.2:1), if that much were left at the end of the aerobic phase. Note that the alum dosage of reactor #4 was more than enough for chemical precipitation without any biological phosphorus removal.

(2) Favorable BPR stage - Stage I

During the period December 10, 1986 to January 13, 1987 (day 7-41), the units were provided sodium acetate feed of 40 mg/l carbon (favorable BPR condition) to investigate the effects of alum additions under this condition.

(3) Unfavorable BPR stage - Stage II

From January 14 to February 11, 1987 (day 42-70) the units were not provided acetate feed (unfavorable BPR condition) to investigate the effects of alum additions under this condition. Sodium bicarbonate (50 mg/l CaCO3) was provided to raise the alkalinity level because significant drops of pH levels were observed after the discontinuing the acetate feed. The sodium bicarbonate feed was added during the anaerobic phase using acetate pump for convenience.

(4) Partially favorable BPR stage - Stage III

From February 23 to April 2, 1987 (day 82-120) the units were provided sodium acetate feed of 15 mg/l carbon and same strength of sodium bicarbonate as in stage II. This stage was used to investigate the effects of alum additions under this partially favorable BPR condition. The strength of 15 mg/l carbon was determined by changing the concentration of acetate feed to the control unit after the end of stage II and testing effluent orthophosphate (PO4-P) concentration by Hach Amino Acid Method. The strength of acetate feed was

adjusted until the effluent PO4-P concentration was on the margin of 1 mg/l limit to investigate the optimal strength of acetate feed for BPR. The operation conditions and data are given in Appendix A-2.

Experimental Methods

(1) Maintenance

a) Sodium acetate (21.35 g/l) was prepared in a one liter reagent bottle for each reactor. It was made fresh every 5 days.

b) Alum was prepared in a one liter reagent bottle for each alum unit (0.43, 0.85, and 1.70 g/l Al for reactors #2, #3, and #4, respectively). It was made fresh every 6 days.

c) The compressed nitrogen gas cylinder was replaced every 10 days.

d) The pump tubes of the Autoanalyzer (acetate feed pump) were replaced once a month.

e) Mixed liquor was wasted everyday near the end of the aerobic phase, before the alum feed.

g) Air flow rates were adjusted to maintain approximately 5 mg/l of dissolved oxygen (DO) concentrations at the end of the aerobic phase.

f) Equal amounts of sodium acetate and alum were added to each reactor and monitored by the marked reagent bottles. The walls of each reactor were marked to indicate volumes; water levels of the reactors were monitored by observing water levels in the sample tubes.

(2) Sampling

a) Unfiltered influent samples were grabbed once a week and preserved by adding concentrated sulfuric acid to pH less than 2 for total phosphorus (TP) and total Kjeldahl nitrogen (TKN) analyses. Filtered samples were collected twice a week and filtered through WHATMAN GF/F glass microfiber filters for orthophosphate (PO4-P), ammonia nitrogen (NH3-N), and oxidized nitrogen (NOx-N) analyses.

b) Anaerobic phase mixed liquor samples were collected twice a week, 15 minutes before the end of the FILL period. After being centrifuged and filtered, they were frozen until PO4-P, NH3-N and NOx-N analyses were run.

c) Aerobic phase mixed liquor samples were collected twice a week, 15 minutes before the end of the REACT period. The same procedure and analyses were conducted as for anaerobic samples.

d) Effluent samples were collected about two minutes after the beginning of the DRAW period twice a week. It was desirable to wait until solids in the standpipes had been flushed out before sampling. The same procedures as for influent samples were conducted for PO4-P, NH3-N, NOx-N, TKN, and TP analyses.

(3) Analyses

PO4-P, NH3-N, and NOx-N analyses were conducted twice a week (see Table 4). TP and TKN were digested and analyzed once a week. An ORION SCIENTIFIC auto analyzer was used for the analysis. This included an AS-140 sampler, AP-200 peristaltic pump, AR-200 recorder, and two AC-100 colorimeters and combination analytical cartridges. The CFA-PC data handling system was also used to compute the data. Spiked and duplicate samples were used in each analytical run for quality control. Analyses were performed according to the Orion Scientific Instruments Manual. These were based on the methods approved by EPA (1979) and Standard Methods (1985).

The pH of influent, effluent, and mixed liquors for anaerobic and aerobic periods were measured twice a week using an ORION 701A digital pH/mV meter. The concentrations of BOD5 of the influent, effluent, and sodium acetate feed were determined once a week following the procedure in Standard Methods (1985), part 507, including nitrification inhibition. The dissolved oxygen (DO) levels were measured with a WESTON and STACK 330 Dissolved Oxygen Analyzer. The DO concentrations were checked during the anaerobic phase, but this measurement was terminated after two weeks because of the constant zero level.

TABLE 4. Analyses of SBR Samples

Analysis	Sample	Frequency (per week)
PO4-P (filtered)	Influent	2
	Anaerobic phase	2
	Aerobic phase	2
	Effluent	2
NH3-N (filtered)	Influent	2
	Anaerobic phase	2
	Aerobic phase	2
	Effluent	2
NOx-N (filtered)	Influent	2
	Anaerobic phase	2
	Aerobic phase	2
	Effluent	2
TP (unfiltered)	Influent	1
	Effluent	2
TKN (unfiltered)	Influent	1
	Effluent	2
pH	Influent	2
	Anaerobic phase	2
	Aerobic phase	2
	Effluent	2
BOD5	Influent	1
	Effluent	1
SS	Influent	1
	Mixed Liquor	1
	Effluent	1
VSS	Mixed Liquor	1
SVI	Mixed Liquor	1

Suspended solids (SS) and volatile suspended solids (VSS) concentrations were determined according to Standard Methods, part 209 C and D using WHATMANGF/C glass microfiber filters. The suspended solids of influent, effluent, and mixed liquor were measured once a week. The sludge volume index (SVI) was determined once a week.

RESULTS AND DISCUSSION

Influent Characteristics and Operating Conditions

The system influent was the primary clarifier effluent of the Mason Farm Treatment Plant. The average concentrations and standard deviations of its various constituents for each stages are summarized in Table 5. The system influent in this study contains 80 mg/l SS, 110 mg/l BOD5, 30 mg/l TKN, 17 mg/l NH3-N, and 5 mg/l TP, and could be classified as a weak wastewater. The average temperature of the system influent was low, 15^{o}C, through the period of this study.

The average levels of mixed liquor suspended solids (MLSS), as shown in Table 6, seem in the same range for all units in Stage I (1310-1540 mg/l). Lower levels of MLSS (760-1200 mg/L) were observed in Stage II, especially reactor #3, as illustrated in Figure 4. Because of the low levels of MLSS in Stage II, the MCRT was increased in Stage III from 12 days (the MCRT of Stages I and II) to 25 days to increase the MLSS levels in Stage III. However, only reactor #1 showed significant increase of MLSS levels in Figure 4.

The levels of MLVSS also showed the similar trend as MLSS did, as shown in Table 6 and Figure 5. Since the bound water in aluminum hydroxide would not release in the MLSS

TABLE 5. AVERAGE CHARACTERISTICS OF SYSTEM INFLUENT+

PARAMETER		T*	I	II	III
pH	AVG	7.2	7.3	7.3	7.1
	STD	0.1	0.1	0.1	0.1
NH3-N	AVG	16.8	16.6	17.0	16.0
	STD	4.8	4.8	4.6	4.6
NOx-N	AVG	0.2	0.1	0.2	0.2
	STD	0.2	0.1	0.2	0.2
PO4-P	AVG	3.1	3.1	2.7	3.3
	STD	1.0	1.1	0.9	0.7
TP	AVG	5.4	5.3	5.3	5.5
	STD	1.5	1.8	1.4	0.7
TKN	AVG	28	24	30	27
	STD	7	8	6	4
BOD5	AVG	113	109	93	141
	STD	27	19	25	16
SS	AVG	81	67	79	86
	STD	30	23	17	28

\+ ALL VALUES EXCEPT pH ARE EXPRESSED IN mg/l

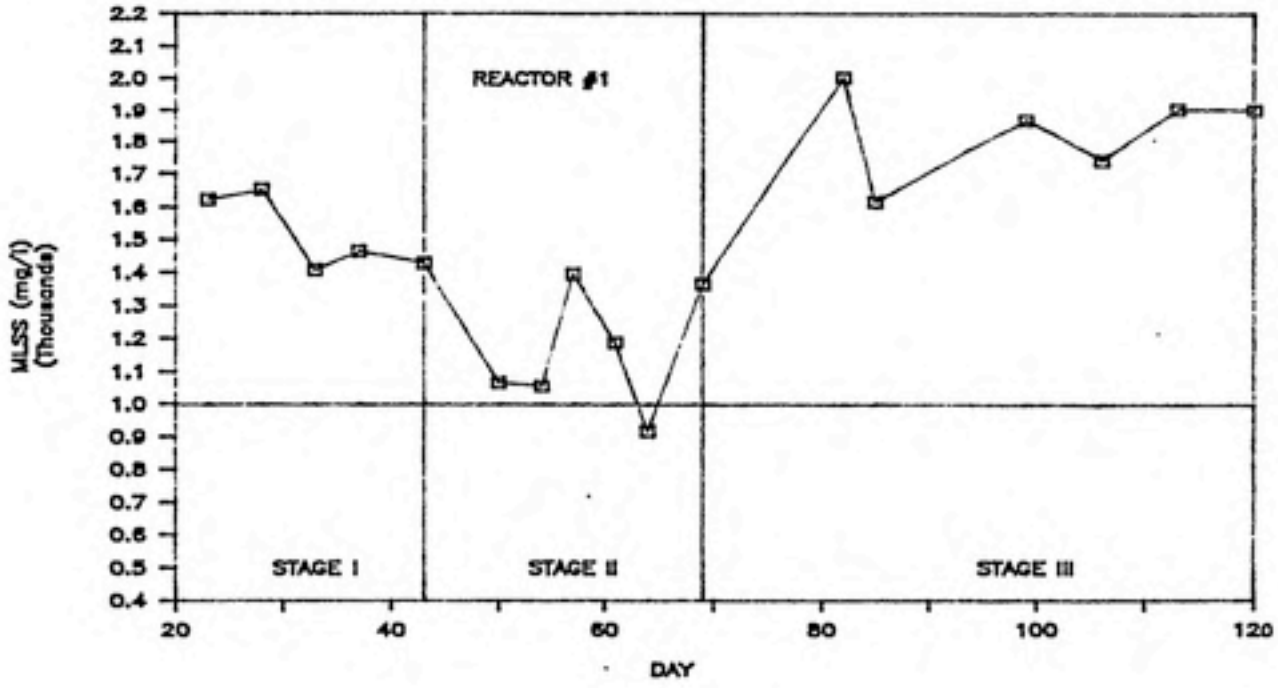
* T : ENTIRE EXPERIMENT PERIOD

TABLE 6. AVERAGE OPERATING CONDITIONS

PARAMETER		#1		#2		#3		#4	
ALUM DOSAGE (mg/l)		0		26		52		104	
	*STAGE	AVG	STD	AVG	STD	AVG	STD	AVG	STD
MLSS (mg/l)	I	1540	100	1400	95	1310	140	1430	200
	II	1200	180	1010	210	760	200	1010	240
	III	1840	130	1240	260	1080	290	1290	190
MLVSS (mg/l)	I	1310	80	1170	90	1100	90	1120	125
	II	1000	180	820	180	630	170	750	170
	III	1350	100	920	160	770	195	860	110
VSS (%) MLVSS/MLSS	I	85	2	84	2	85	2	78	3
	II	82	4	81	3	83	3	75	5
	III	73	2	75	3	72	3	67	2
SVI (ml/g)	I	160	6	110	10	90	8	80	6
	II	160	21	110	18	80	22	70	19
	III	190	46	80	8	60	12	60	10
MCRT (DAY)	I	12		12		12		12	
	II	12		12		12		12	
	III	25		25		25		25	

* STAGE I : ACETATE FEED IS 40 mg/l C
STAGE II : ACETATE FEED IS 0 mg/l C
STAGE III : ACETATE FEED IS 15 mg/l C

FIG.4 COMPARISON OF MLSS



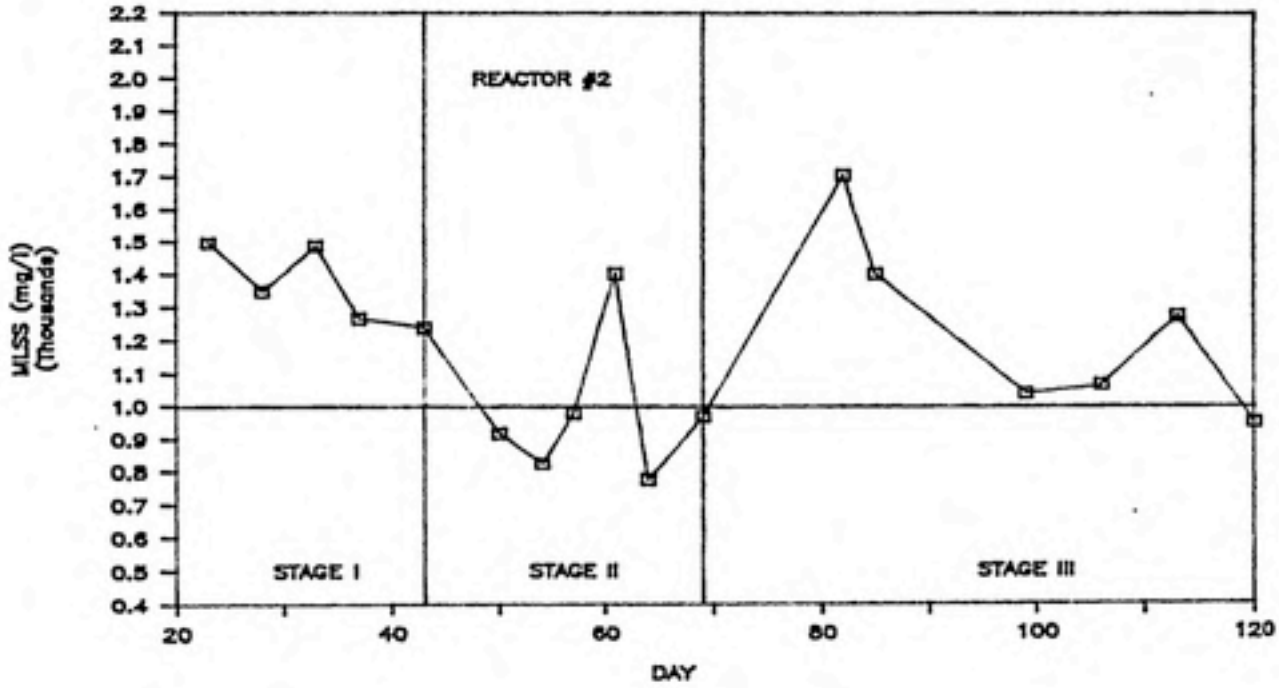
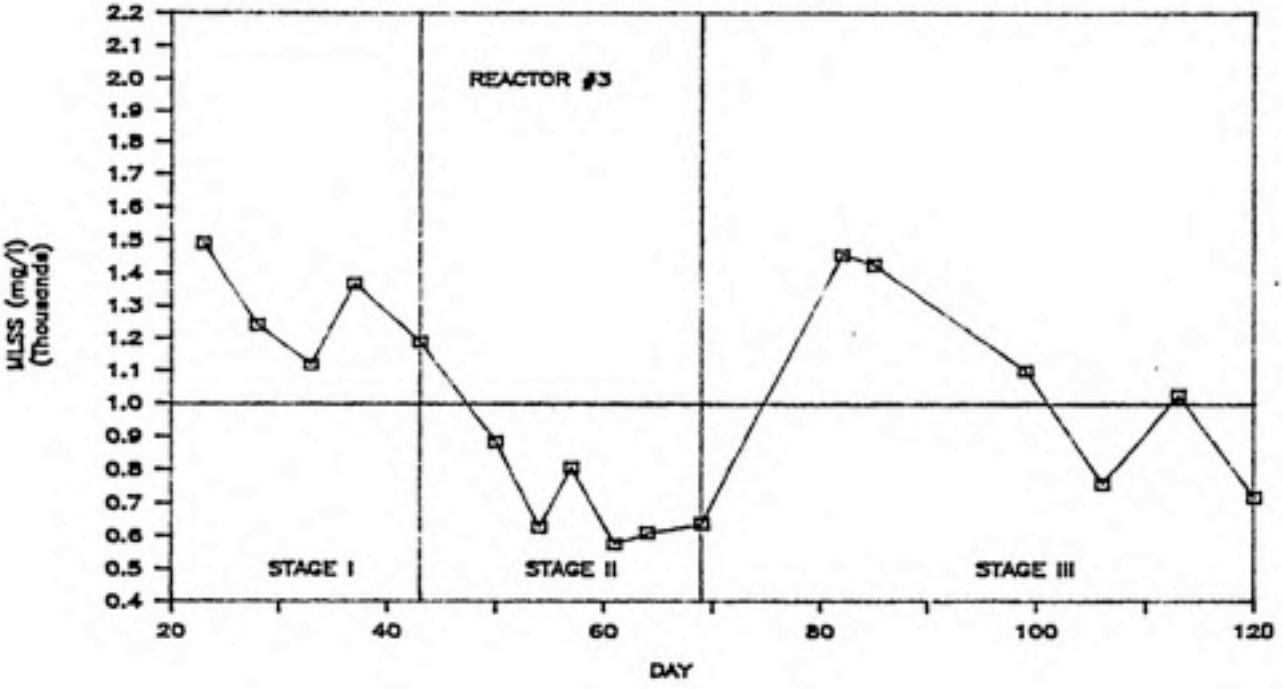


FIG.4 COMPARISON OF MLSS (cont.)



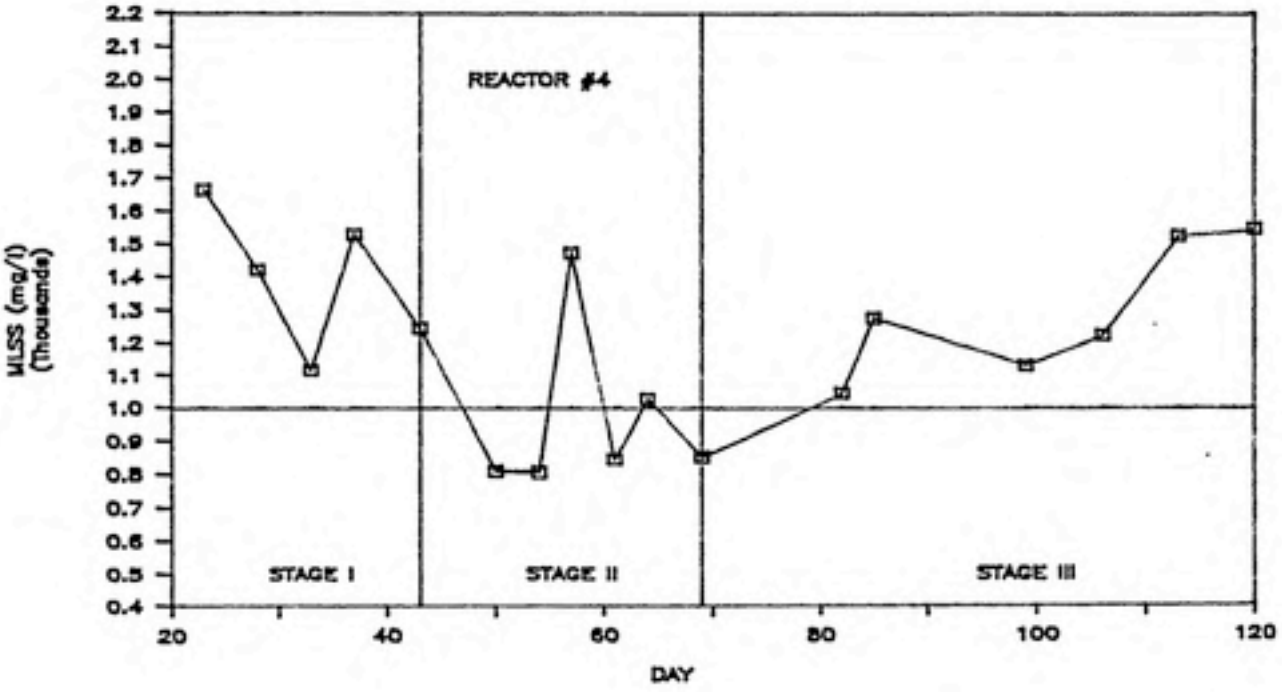
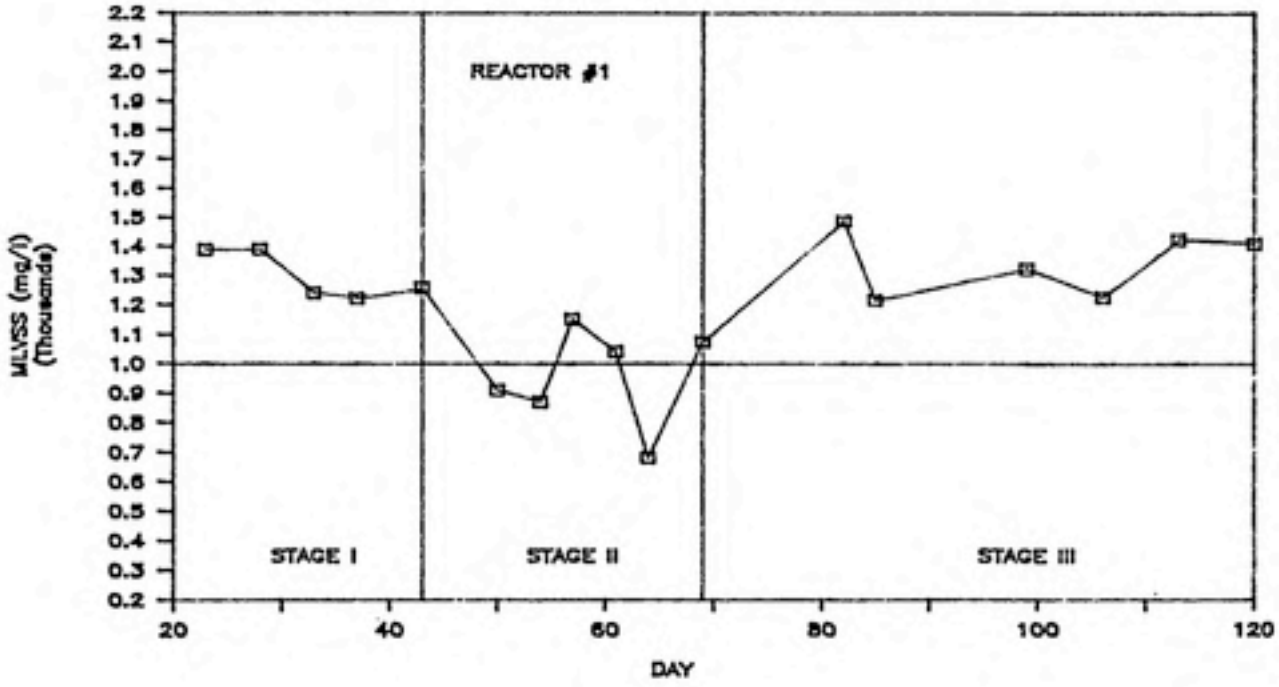


FIG. 5 COMPARISON OF MLVSS



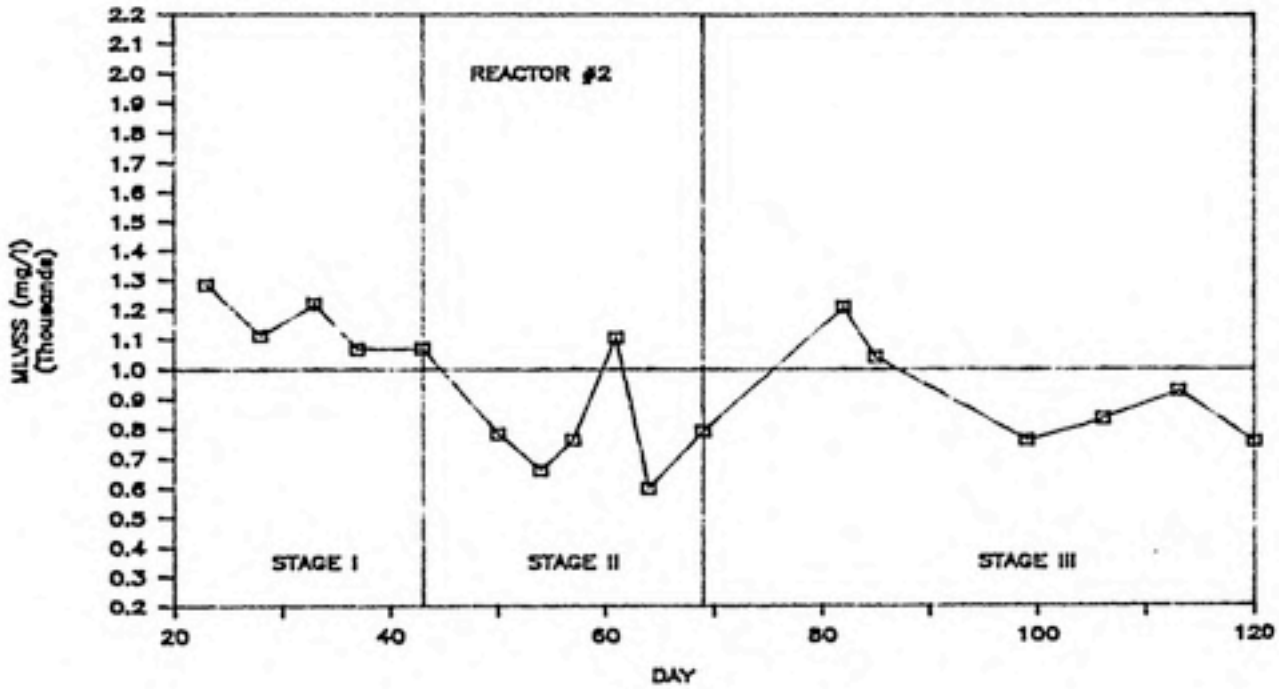
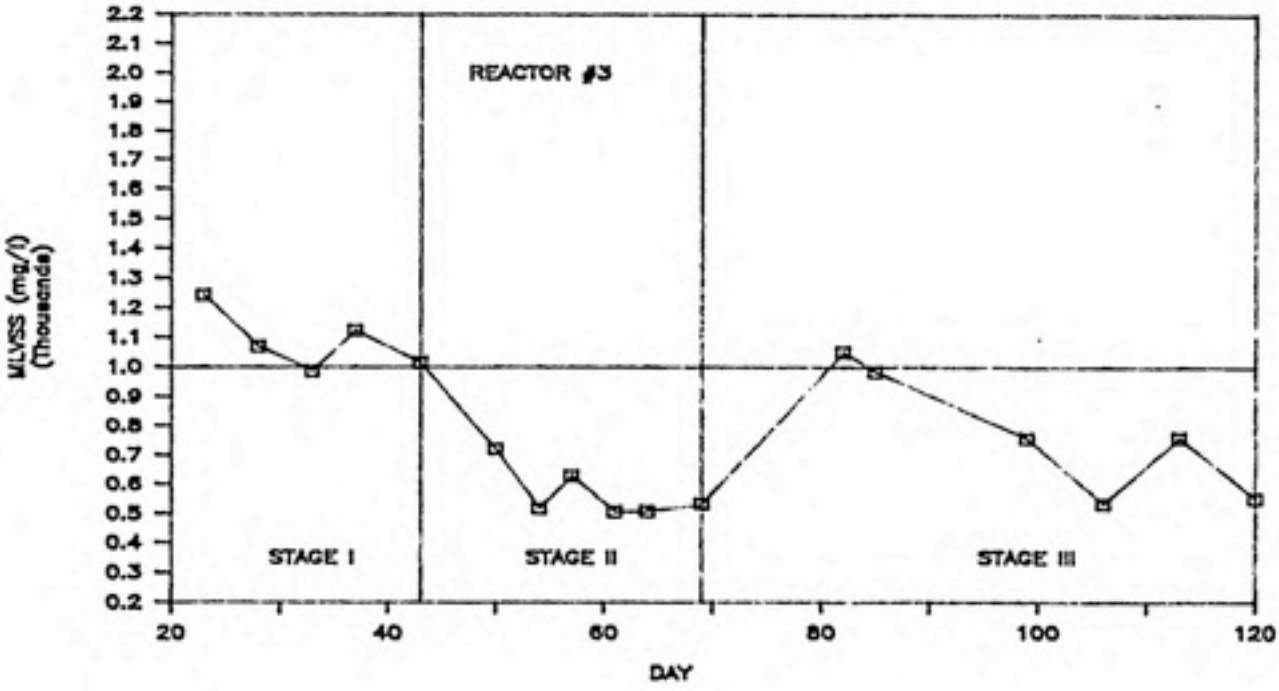
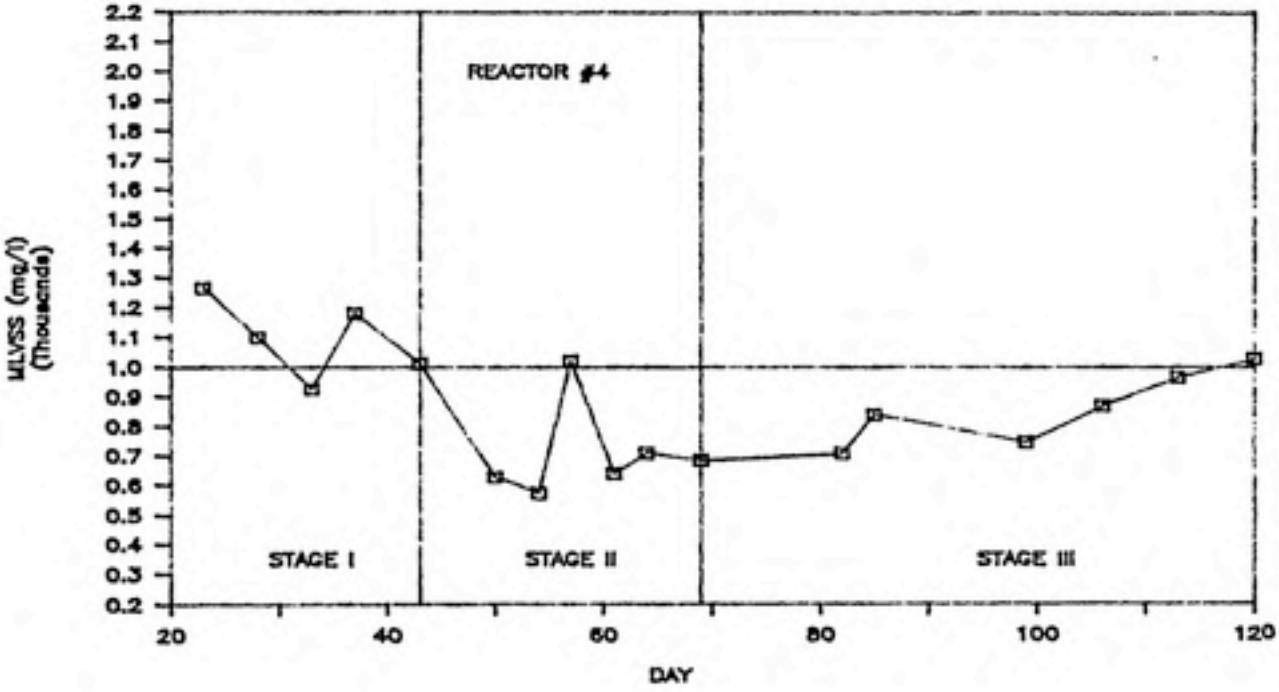


FIG. 5 COMPARISON OF MLVSS (cont.)





test (103°C) until in the MLVSS test (550°C), the organic, MLVSS levels of the alum units in this experiment were lower than the levels shown in Table 6. In another experiment (not shown here), 15 to 20 percent of weight of alum precipitate at 103°C was lost upon determining VSS at 550°C.

It is unclear why reactor #3 showed significant lower levels of MLSS and MLVSS in Stage II, and why only the control unit (reactor #1) showed significant increase of MLSS and MLVSS from the increase of MCRT in Stage III. The turbid effluents in reactor #3, as shown in Table 7, might explain the lowest levels of MLSS in reactor #3. However, from the excellent BOD removals (96-99%) for all units in Table 8, the increase of turbidity in reactors #3 and #4 did not result in a proportional increase in effluent BOD5 concentrations. This suggests that most of the effluent solids in the alum units may be inorganic solids. Therefore, the significant lower levels of MLVSS in reactor #3 may not be due to the wash out of the organic solids in turbid effluents, and more studies need to be conducted. The detailed effluent suspended solids and BOD data may be found in Appendix A-5.

According to Table 7, the effluent suspended solids concentrations generally increased when more alum was added. However, reactor #3 showed poorer solids removal performance (67-76%) than did reactor #4 (75-81%). The reason for this

TABLE 7. AVERAGE EFFLUENT SUSPENDED SOLIDS PERFORMANCE

PARAMETER	STAGE		FEED	#1	#2	#3	#4
ALUM DOSAGE (mg/l)			-	-	26	52	104
SS (mg/l)	I	AVG	74	7	9	19	16
		STD	23	2	1	2	6
	II	AVG	79	9	10	25	22
		STD	17	2	4	9	4
	III	AVG	86	6	12	24	15
		STD	28	2	4	7	3
REMOVAL (%)	I	AVG	-	91	89	76	81
	II	AVG	-	90	88	73	75
	III	AVG	-	93	83	67	76

TABLE 8. AVERAGE BIOCHEMICAL OXYGEN DEMAND PERFORMANCE

PARAMETER	STAGE*		FEED+	#1	#2	#3	#4
ALUM DOSAGE (mg/l)				0	26	52	104
BOD5 (mg/l)	I	AVG	175	2	3	2	1
		STD	19	1	<1	1	1
	II	AVG	93	3	3	3	2
		STD	25	1	1	1	1
	III	AVG	166	3	4	4	3
		STD	16	1	1	<1	1
REMOVAL (%)	I	AVG	-	99	98	98	99
	II	AVG	-	97	96	97	98
	III	AVG	-	98	97	97	98

+ FEED BOD5 = PRIMARY EFFLUENT BOD5 + ACETATE FEED BOD5

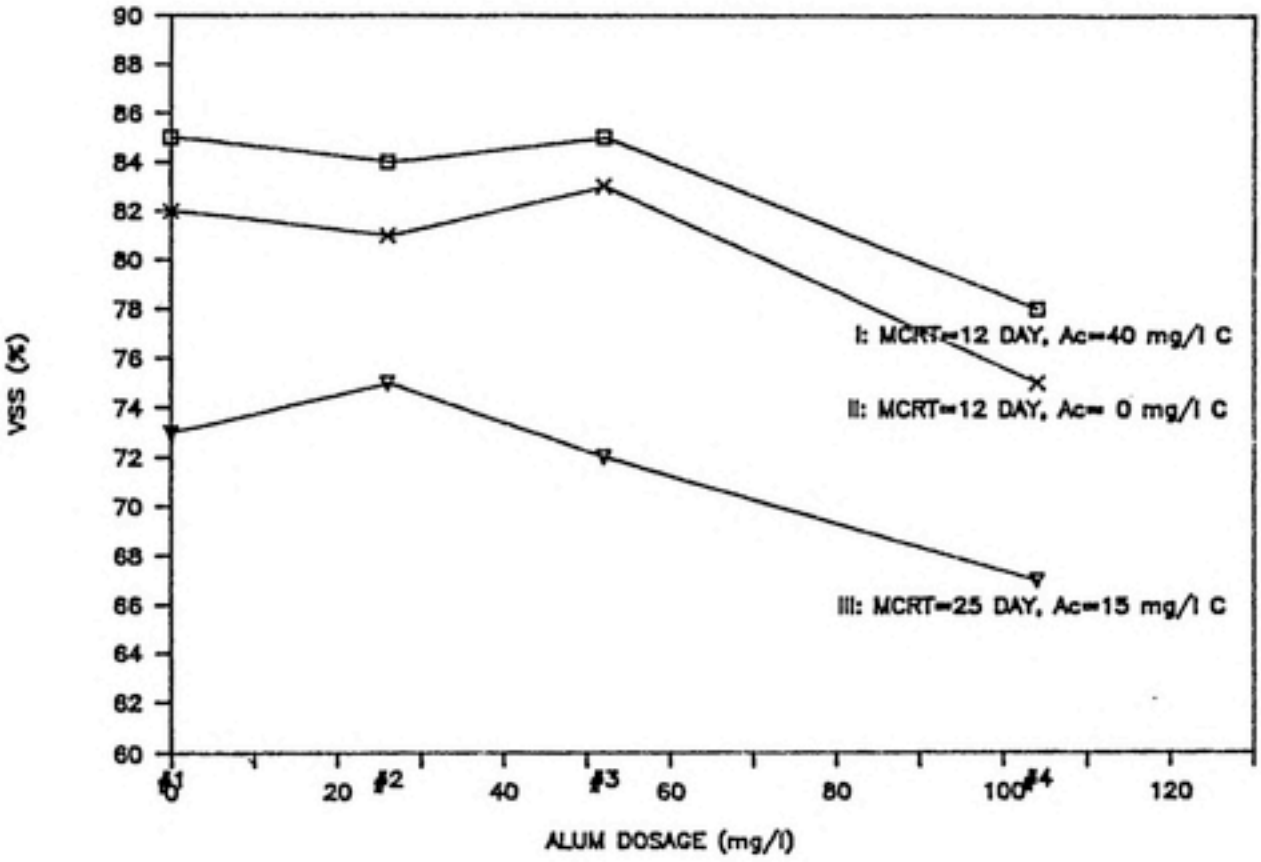
* STAGE I : ACETATE FEED BOD5 = 66 mg/l (38 % OF FEED BOD5)
STAGE II : ACETATE FEED BOD5 = 0 mg/l (0 % OF FEED BOD5)
STAGE III : ACETATE FEED BOD5 = 25 mg/l (15 % OF FEED BOD5)

observation is unclear. Turbid effluents from alum units have also been observed by Barth (1967), and Gray (1976). Perhaps, a brief period of gentle agitation prior to solids separation should be used, as suggested by EPA (1976), to promote flocculation and prevent the chemical floc from disintegrating by mixing. The excellent performance of suspended solids removal for the control unit has also been shown at the full-scale SBR plant in Culver, Indiana (1985).

In Table 6, significant drops of the average percentages of mixed liquor volatile suspended solids (VSS) were observed in Stage III (67-75%) compared with Stages I and II (75-85%), as shown in Figure 6. The lower VSS percentages in Stage III may due to the longer MCRT, in spite of increased acetate feed, because the higher MCRT leads to more endogenous respiration. If the bound water in aluminum hydroxide is excluded, the percentages of VSS in the alum units would be even lower. Therefore, the VSS percentages in reactors #2 and #3 actually might be lower than the control unit. The reason for the lowest percentage of VSS of reactor #4 in all stages is not clear, but it might be because the greatest dosage of alum was fed into reactor #4.

As to settleability, the units receiving alum showed significant lower average SVIs (60-110 ml/g) than the control unit (160-190 ml/g), and as more alum was added lower SVIs

FIG.6 EFFECT OF MCRT ON VSS



were obtained in the alum units, as shown in Table 6. These have also been observed by Eberhardt and Nesbitt (1968), Barth and Ettinger (1967), and Finger (1973). The effect may be caused by an increased sludge density or more effective aggregration by the alum flocs. The detailed data of these solids characteristics are given in Appendix A-4.

Effect of Alum Additions on Phosphorus Removal

(1) Phosphorus Removal by the Control Unit

The data in Table 9 show that the control unit removed 93, 69, and 83 percent of total phosphorus in Stages I, II, and III, corresponding to acetate additions of 40, 0 and 15 mg/l carbon, respectively. This result suggests that the strength of acetate feed may be important to BPR. When the acetate feed was discontinued in Stage II, the percentage of TP removal dropped from 93 to 69 percent. In Stage III, the acetate feed was subsequently resumed at one third of the strength in Stage I, TP removal increased to 83 percent. The importance of acetate on biological phosphorus removal has also been observed by other researchers (Chiesa, 1986; Gerber, 1986).

Since effluent TP concentrations did not be measured until day 30, the variation of effluent TP in Stage I, as shown in Figure 7, can be hardly compared with the other two stages. If PO4-P concentrations at the end of aerobic phase were used to show the performance of phosphorus removal, as illustrated in Figure 8, the control unit showed constant low effluent PO4-P in Stage I, constant higher PO4-P in Stage II, and large variations of PO4-P in Stage III. Although the reason for the bigger P variations in Stage III, as shown in Figures 7 and 8, is unclear, the higher strength of acetate

TABLE 9. PHOSPHORUS REMOVAL BY THE CONTROL UNIT

PARAMETER		STAGE I	STAGE II	STAGE III
ACETATE ADDITION (mg/l C)		40	0	15
FEED				
TP (mg/l)	AVG	5.3	5.3	5.5
	STD	1.8	1.4	0.7
EFFLUENT				
TP (mg/l)	AVG	0.4	2.1	1.4
	STD	0.2	0.7	1.3
REMOVAL (%)	AVG	93	69	83

FIG.7 EFFLUENT TP OF THE CONTROL UNIT

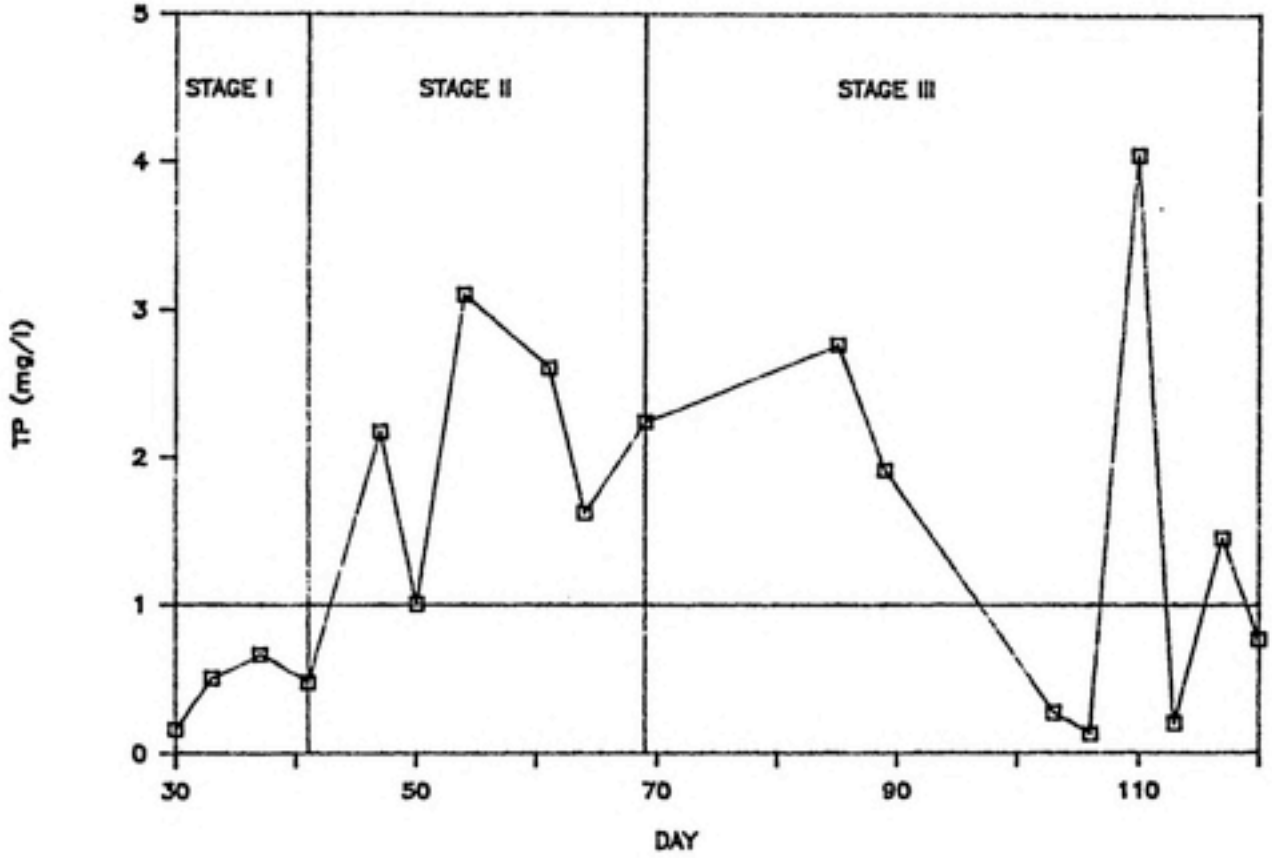
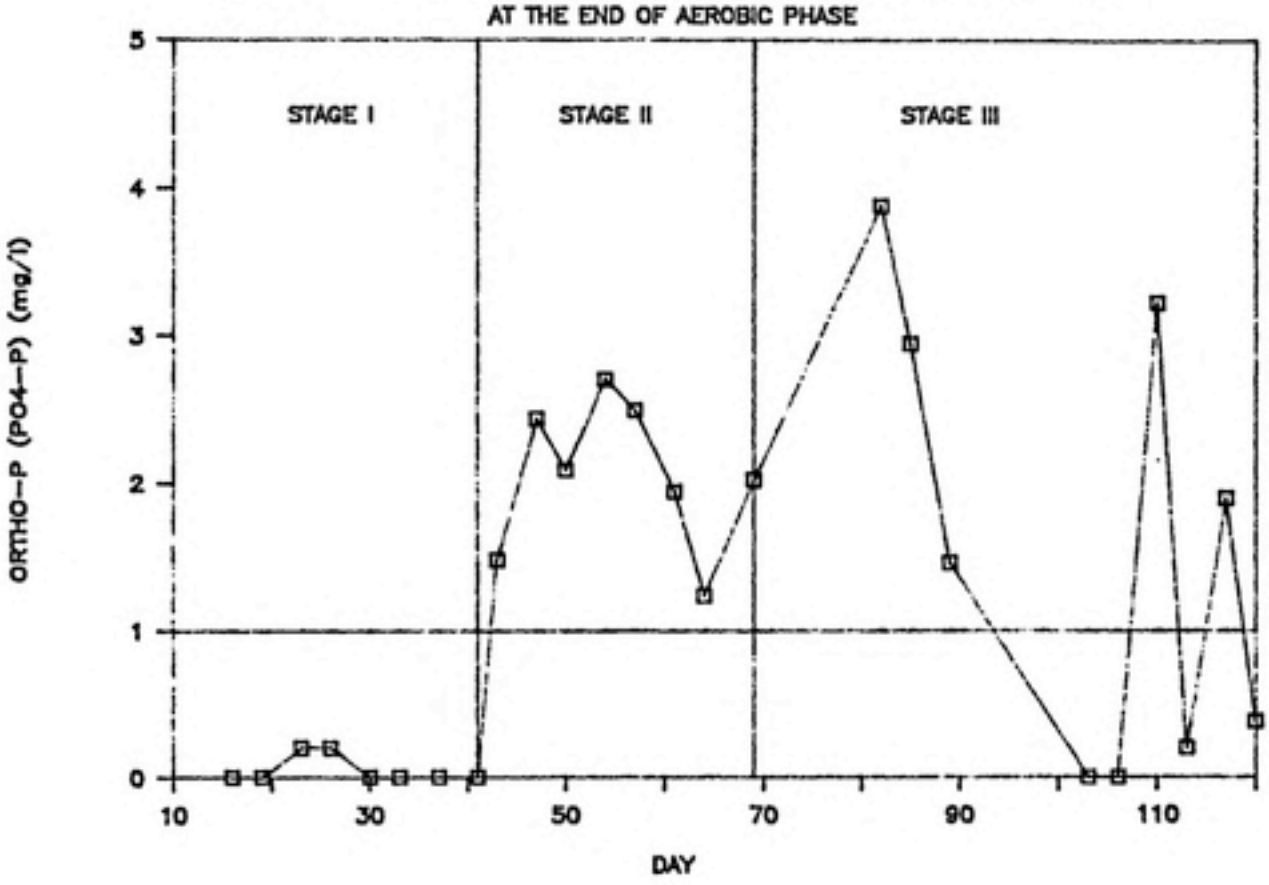


FIG.8 ORTHO–P OF THE CONTROL UNIT



feed was added, the more constantly good P removal was observed. therefore, the importance of acetate feed on BPR can be assured.

When the low average P-release (4.1 mg/l) during the anaerobic phase was observed in Stage II, as shown in Table 10, poor aerobic P-uptake during the aerobic phase was observed. This suggests that low P-release during anaerobic phase could predict poor P-uptake during the aerobic phase. However, when the same range of average P-release during anaerobic phases were observed (13.4 and 12.7 mg/l in Stages I and III, respectively), the PO4-P concentrations at the end of aerobic phases were significantly different (0.1 and 1.6 mg/l in Stages I and III, respectively). The difference in P-uptake performances suggests, that high range of P-release during anaerobic phase does not necessarily guarantee good P-uptake during aerobic phase and that other factors must be involved.

For good phosphorus removal, a ratio of BOD5 to TP greater than 20 to 25 has been suggested by Tetreault et al.(1986). The average ratios in these experiments were 37, 17, and 31 during the three stages, respectively (see Table 10). In Stage III, this ratio is higher than 25 and approximately in the same range as in Stage I. Nevertheless, phosphorus removal by the control unit in Stage III was pooer than

TABLE 10. PHOSPHORUS PERFORMANCE OF THE CONTROL UNIT AT THE END OF ANAEROBIC AND AEROBIC PHASES

		STAGE		
PARAMETER		I	II	III
ACETATE ADDITION (mg/l C)		40	0	15
ANAEROBIC PHASE PO4-P (mg/l)	AVG	13.4	4.1	12.7
	STD	5.2	1.5	4.8
AEROBIC PHASE PO4-P (mg/l)	AVG	0.1	2.0	1.6
	STD	0.1	0.5	1.4
* FEED BOD5/TP	AVG	37	17	31

* FEED BOD5 = PRIMARY EFFLUENT BOD5 + ACETATE FEED BOD5

Stage I. In these two stages, the phosphorus loadings were similar (5.3 and 5.5 mg/l, see Table 9) and feed BOD concentrations were also similar (175 and 166 mg/l, see Table 8). The only clear difference is that higher strength of acetate feed was provided in Stage I (40 mg/l carbon) than in Stage III (15 mg/l carbon). The better BPR performance with higher acetate feed in Stage I suggests that the concentration of acetate may play a more important role on on BPR than the strength of wastewater. It is also shown in the study of Gerber et al. (1986) that acetate promotes more phosphorus removal than does glucose addition at the same equivalent COD concentration.

However, the longer MCRT in Stage III may or may not affect the phosphorus removal performance. If the longer MCRT is not favorable to phosphorus-accumulating organisms, the acetate strength of 15 mg/l in Stage III may be enough to the MCRT was same, but performance differed greatly. Thus, the importance of acetate feed on phosphorus removal can be assured. More studies need to be conducted to investigate the effects of MCRT on BPR and the optimal dosage of acetate feed for BPR.

(2) Phosphorus Removal by the Units Receiving Alum

Significantly low average P-releases during the anaerobic phases in Stage II, as shown in Table 11 and Figure 9, were observed in the alum units as well as the control unit. This suggests that acetate plays an important part on P-release in the alum units, as well as in the control unit. Significant average P-releases were observed in the alum units during anaerobic phase (5.8-10.5 mg/l) in Stages I and III. The more alum added,the lower theobservedPO4-P releasein all stages, but the effect of alum additionson suppressing P-release is less drastic than the discontinuity of acetate feed in Stage II.

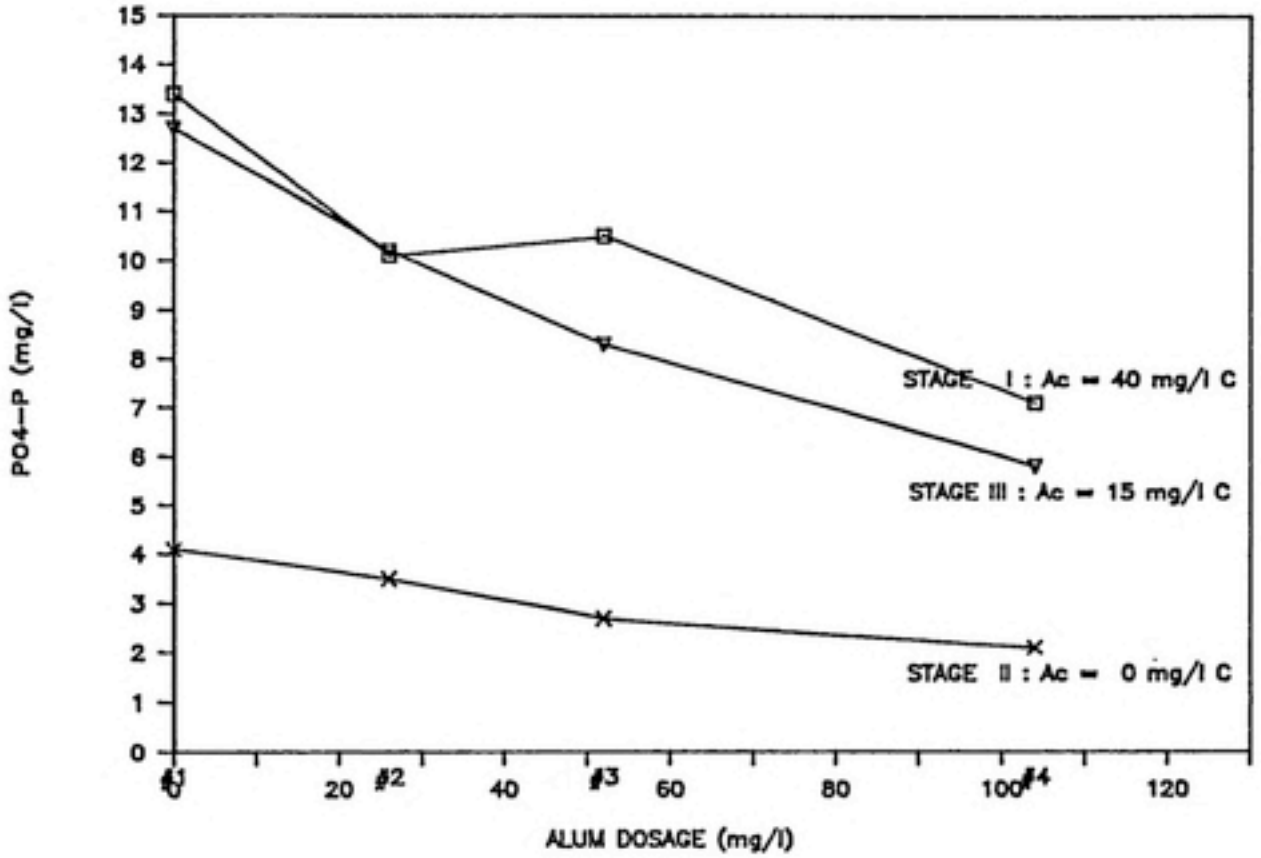
The lower average PO4-P concentrations during anaerobic phases in the alum units could be caused by precipitation or adsorption of released phosphate by Al (III). However, if Al (III) precipitation or/and adsorption is responsible, one would expect the PO4-P concentrations in the liquid of the alum units during anaerobic phase in Stage II to be much lower because of the amount of alum present should be enough to precipitate (or adsorb) the low phosphorus concentration revealed by the control unit (see Table 11). The PO4-P concentrations in Stage II suggest strongly that the extent of precipitation or adsorption was small. The suppression of P-release in the anaerobic alum units also could be caused by

TABLE 11. PHOSPHORUS PERFORMANCE AT THE END OF ANAEROBIC PHASES+

ACETATE FEED	STAGE		FEED	#1	#2	#3	#4
(mg/l C)				ALUM DOSEAGE (mg/l)			
				0	26	52	104
40	I	AVG	3.1	13.4	10.1	10.5	7.1
		STD	1.1	5.2	3.7	3.8	2.9
0	II	AVG	2.7	4.1	3.5	2.7	2.1
		STD	0.9	1.5	1.7	1.4	1.2
15	III	AVG	3.3	12.7	10.2	8.3	5.8
		STD	0.7	4.8	3.7	3.5	3.7

+ ALL VALUES EXPECT ALUM DOSAGES ARE EXPRESSED IN mg/l AS PO4-P

FIG.9 EFFECT OF ALUM AND ACETATE ON P–RELEASE



other factors, perhaps the interference of aluminum ions with the mechanisms of P-release.

From Table 12, the oxidized nitrogen concentrations (NOx-N) at the end of the anaerobic phases were undetectable in all units. This verifies the truly anaerobic condition in this phase. However, these units would be anoxic at the beginning of anaerobic phase because there would be some nitrate in sludge retained in the system. The presence of nitrate in the anaerobic phase would inhibit P-release (Hascoet,1985). However, the concentration of NOx-N at the end of the aerobic phase decreased with increase in alum dosage. So, the depression of P-release in the alum units by the inhibitory effect of nitrate would not be a reasonable hypothesis.

Both P-release and excess P-uptakes were observed in Stages I and III, as shown in Table 11, regardless of what mechanisms caused the lower P-release in alum units. Note that reactor #3 and #4 showed good P-uptake throughout the experiment, even in Stage II, and reactor #2 showed better P removal than the control unit (reactor #1) in all stages. This suggests that the addition of alum could increase the reliability of BPR processes and that addition of more alum should decrease the effects of unfavorable BPR conditions (e.g. reduction in the strength of acetate in wastewater feed).

TABLE 12. OXIDIZED NITROGEN DATA AT THE END OF ANAEROBIC AND AEROBIC PHASES+

		#1	#2	#3	#4
ALUM DOSAGE		0	26	52	104
STAGE		NOx-N (ANA.)*			
I	AVG	0.0	0.0	0.0	0.0
	STD	0.0	0.0	0.0	0.0
II	AVG	0.0	0.0	0.0	0.0
	STD	0.0	0.0	0.0	0.0
III	AVG	0.0	0.0	0.0	0.0
	STD	0.0	0.0	0.0	0.0
		NOx-N (AER.)**			
I	AVG	5.3	5.1	4.5	3.5
	STD	2.0	1.6	1.2	1.3
II	AVG	7.2	6.6	3.9	1.5
	STD	1.5	1.4	1.9	0.8
III	AVG	6.6	6.1	4.1	1.3
	STD	1.3	1.3	0.7	0.4

\+ ALL VALUES ARE EXPRESSED IN mg/l

* (ANA.) - ANAEROBIC PHASE
** (AER.) - AEROBIC PHASE

From the literature and performance of the control unit, the P-release in the anaerobic phase is an important step for BPR during the aerobic phase. Since the relative importance of BPR and alum precipitation in the alum units is hard to identify in this study, the P-release during the anaerobic phase was used as an indication of the activities of phosphorus-removal organisms. Considering the drop in P-release during Stage II and resumption of P-release during Stage III in all units, additions of alum seem to have no obvious adverse effect on the activities of phosphorus-accumulating organisms. This also can be seen from the P removal performance of reactor #2 because the amount of alum added in this unit is too small to account for the phosphorus removal. The addition of acetate has greater effect on the BPR performance. The detailed phosphorus performances are given in Appendix A-6 and the effluent TP concentrations may be found in Appendix A-5.

(3) Effectiveness of Alum Precipitation

For aluminum phosphate (AlPO4) precipitation, the theoretical molar ratio of alum added per mole of phosphorus removed is one. A molar ratio less than one would suggest a contribution from BPR. In Table 13, the molar ratios of reactor #2, which are based on the difference of influent TP and effluent PO4-P concentrations, are less than 1.0 for all stages (0.62, 0.85, and 0.51 in Stages I, II, and III, respectively) demonstrating the contribution of BPR. The effluent PO4-P concentrations were used to approximate soluble phosphorus concentrations. These molar ratios were calculated assuming no suspended phosphorus in the effluent to eliminate the interaction effect of effluent suspended solids on TP concentrations because the presence of high phosphorus-content solids in effluent would increase TP concentrations.

Since in this experiment constant alum dosages were used without trying to match influent phosphorus concentrations, some alum units with very low effluent P could be overdosed. Therefore, the molar ratios of reactors #3 and #4 greater than 1.0 do not necessarily mean less or no BPR involved, or inefficient precipitation of aluminum phosphate. With nearly 100 percent phosphorus removal in some alum units, the molar ratios could be overestimated because it could have been possibleto achieve this performance with loweralum dosage.

TABLE: 13 EFFLUENT PHOSPHORUS PERFORMANCE

PARAMETER	STAGE		FEED	#1	#2	#3	#4
ALUM DOSE (mg/l)			-	0	26	52	104
PO4-P (mg/l)	I	AVG	3.1	<0.1	<0.1	<0.1	<0.1
		STD	1.1	<0.1	<0.1	<0.1	<0.1
	II	AVG	2.7	2.0	1.0	0.4	<0.1
		STD	0.9	0.5	0.5	0.2	<0.1
	III	AVG	3.3	1.6	<0.1	0.0	0.0
		STD	0.7	1.4	0.2	0.0	0.0
REMOVAL (%)	I	AVG	-	~100	~100	~100	~100
	II	AVG	-	52	83	98	100
	III	AVG	-	81	~100	100	100
+MOLAR RATIO	I	AVG	-	-	*0.62	*1.24	*2.48
	II	AVG	-	-	0.85	1.31	*2.56
	III	AVG	-	-	*0.51	*1.02	*2.03

+ BASED ON THE DIFFERENCE OF FEED TP AND EFF. PO4-P

* OVERESTIMATED VALUE : DEFINED IN TEXT

TABLE. 13 EFFLUENT PHOSPHORUS PERFORMANCE (CONT.)

PARAMETER	STAGE		FEED	#1	#2	#3	#4
ALUM DOSAGE (mg/l)			-	0	26	52	104
	I	AVG	5.3	0.4	0.5	0.4	0.3
		STD	1.8	0.2	0.1	0.1	0.1
TP (mg/l)	II	AVG	5.3	2.1	1.1	1.2	0.6
		STD	1.4	0.7	0.4	0.4	0.4
	III	AVG	5.5	1.4	0.5	0.9	0.5
		STD	0.7	1.3	0.1	0.4	0.1
	I	AVG	-	93	91	93	95
REMOVAL (%)	II	AVG	-	69	73	79	87
	III	AVG	-	83	91	81	91
	I	AVG	-	-	0.89	1.34	2.61
++MOLAR RATIO	II	AVG	-	-	1.98	1.64	2.95
	III	AVG	-	-	1.12	1.27	2.24

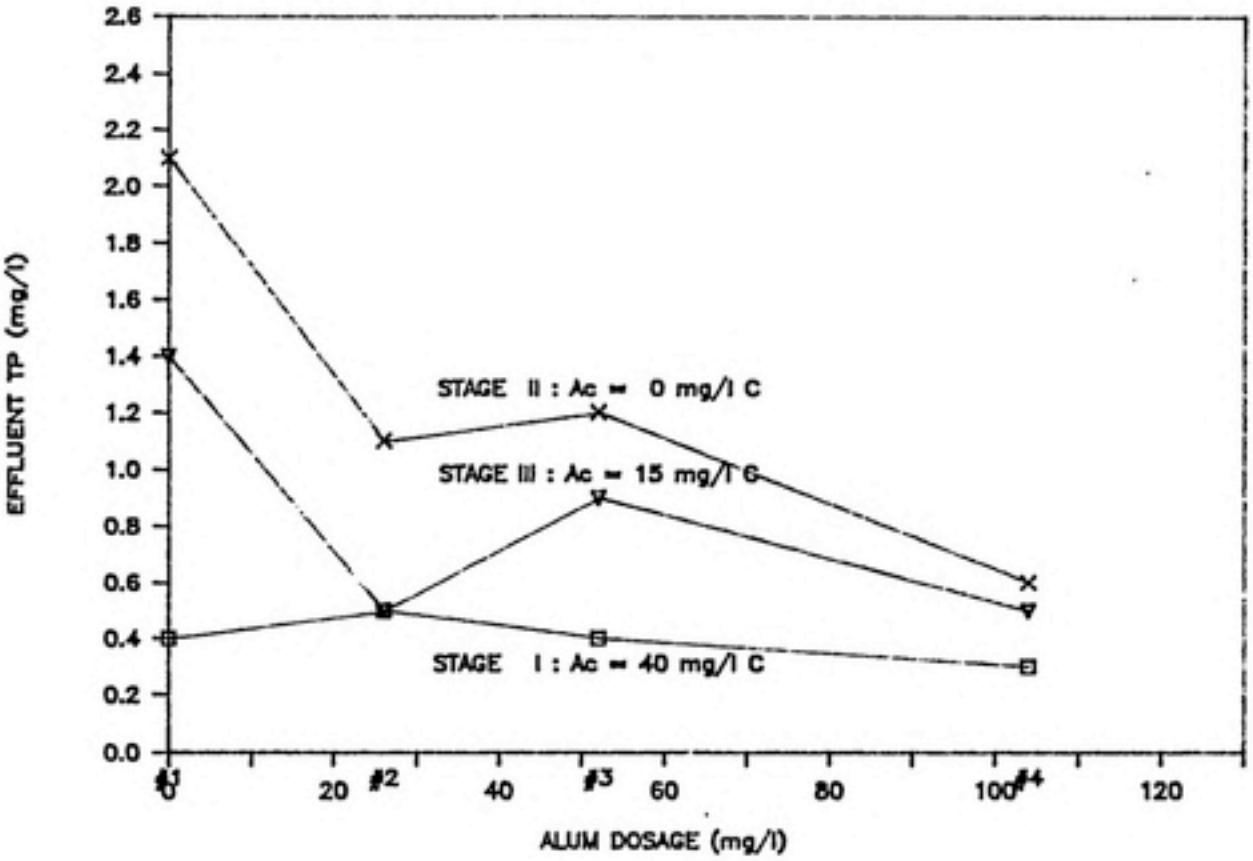
++ BASED ON THE DIFFERENCE OF FEED TP AND EFF. TP

It can be concluded that the molar ratios for reactor #3 and #4 in Stages I and III were overestimated because reactor #2, with lower alum dose, also achieved the same performance (see Table 13). As for the molar ratios of reactor #2 in Stages I and III, it is possible that they too were overestimated because of the nearly 100 percent PO4-P removal in these stages. Since the PO4-P removal of reactors #2 and #3 in Stage II are less than 100 percent, the molar ratios were not overestimated.

In Stage II, the molar ratio of reactor #2 (0.85) is higher than in Stage I (0.62) and Stage III (0.51), showing less BPR activities. This was caused by the discontinuity of sodium acetate feed. However, the extents of BPR and alum precipitation can not be identify from the molar ratios. The relationships between the concentrations of acetate feed and effluent TP, shown in Figure 10, illustrate the importance of acetate feed on phosphorus removal.

If influent and effluent TP concentrations were considered, instead of influent TP and effluent PO4-P concentrations, the molar ratios would be higher (see Table 13). This may due to the effluent suspended biomass, which would be high in phosphorus content after luxury uptake, also, from the suspended Al-P solids. The solids with high phosphorus content would contribute to the effluent phosphorus

FIG.10 EFFECT OF ALUM AND ACETATE ON EFF. TP



concentration in TP analyses, making the removal of effluent suspended solids important. For example, if the effluent suspended solids of reactor #2 contain 5 percent of phosphorus, 8 mg/l of suspended solids would contribute 0.5 mg/l of phosphorus. This would increase the molar ratio from 0.51 to 1.12, which does not demonstrate the contribution of BPR in the combined-treatment. Therefore, it would be more suitable to use effluent soluble phosphorus (or PO4-P) instead of TP concentrations to evaluate BPR technology because the performance of solids removal would affect the effluent TP concentrations.

Therefore, the effect of effluent suspended solids on phosphorus removal could explain why reactor #3 did not show better performance than reactor #2 (see Figure 10). Under the SBRoperation with alum additions, a molar ratio of 6.6 was reported by Ketchum et al. (1987) to obtain acceptable phosphorus concentrations in the effluents. This high value was based on effluent TP concentrations, so it could be due to the turbid effluents instead of the inefficient combined-treatment.

In Table 13, the more alum was added the more phosphorus was removed by precipitation in Stage II. When more BPR was involved in Stages I and III, increase in alum added in the reactors did not improve the phosphorus removal

as much as in Stage II. (The worst phosphorus removal of reactor #3 in Stage III may due to the turbid effluent). Therefore, the addition of alum could help to remove phosphorus when BPR performance fell off, however, when more BPR involves the alum precipitation would not be as effective as when less BPR involves.

Effects of Alum Additions on Nitrification

With respect to nitrification performances, the average concentrations of ammonia nitrogen (NH3-N) and oxidized nitrogen (NOx-N) in effluents are given in Table 14. If poor nitrification occurs in the system, both the NH3-N removal and effluent NOx-N concentration would be low. According to Table 14, poorer nitrification was observed in reactor #3 in the last two stages because higher average NH3-N (3.8-5.8 mg/l) and lower average NOx-N (3.6-5.0 mg/l) were observed compared with the NH3-N (0.1-0.6 mg/l) and NOx-N (6.0-6.8 mg/l) of reactors #1 and #2. As to reactor #4, much worse nitrification was observed in these two stages (II and III) with 10.2-11.7 mg/l and 1.4 mg/l of average NH3-N and NOx-N concentrations, respectively. Thus, the poor nitrification in reactors #3 and #4 clearly shows that the additions of alum caused diminished nitrification.

Since the decreased MLVSS levels of the alum units may not be due to the wash out of solids, as discussed earlier, the poor nitrification in reactors #3 and #4 could be caused by the inhibition of Al(III). This inhibitory effect on nitrifiers by the addition of alum also has been proposed by Long et al. (1971) and Unz et al. (1975). Although Barth et al. (1967) concluded that aluminum ion has no adverse effect on nitrification, their conclusion was based on one month's

TABLE 14. NITRIFICATION PERFORMANCE - COMPARISON OF EFFLUENT AMMONIA AND OXIDIZED NITROGEN+

		FEED	#1	#2	#3	#4
ALUM DOSAGE		-	0	26	52	104
STAGE		AMMONIA NITROGEN (NH3-N)				
I	AVG	16.6	0.3	0.4	1.0	2.9
	STD	5.4	0.6	0.8	1.5	3.8
II	AVG	17.0	0.2	0.6	5.8	11.7
	STD	2.6	0.1	0.6	4.8	3.0
III	AVG	17.0	0.1	0.2	3.8	10.2
	STD	3.8	0.1	0.1	2.6	3.9
		OXIDIZED NITROGEN (NOx-N)*				
I	AVG	0.1	5.3	5.1	4.5	3.5
	STD	0.1	2.0	1.6	1.2	1.3
II	AVG	0.2	6.7	6.0	3.6	1.4
	STD	0.2	1.2	1.1	1.4	0.5
III	AVG	0.2	6.4	6.8	5.0	1.4
	STD	0.2	1.4	1.9	0.6	0.6

* OXIDIZED NITROGEN = NITRATE NITROGEN (NO3-N) + NITRITE NITROGEN (NO2-N)

observation and may not be applicable to the long term effect. Actually, from the comparisons of NH3-N and NOx-N concentrations at the end of aerobic phases, as illustrated in Figures 11 and 12, reactor #4 did not show diminished nitrification until the system was operated for a month (at day 30), which suggests that the inhibitory effect on nitrification by the additions of alum was a long-term effect.

From Figures 11 and 12, reactor #3 did not show poor nitrification until Stage II (at day 57), but still showed better nitrification than reactor #4 did. This shows that when more alum was added, poorer nitrification occurred. However, it is unclear why reactors #3 and #4 showed better nitrification performances between day 80 and 90 in Stage III. Detailed data of NOx-N are given in Appendices A-7 and A-8, respectively.

It is unclear how and why alum affects the nitrification process. Though there may be a pH reduction after alum was added, the average pH of alum units during the anaerobic and aerobic phases were still in the neutral range (6.9-7.3), as given in Table 15. Therefore, the deteriorated nitrification could not be caused by the reduction of pH or alkalinity levels in the alum units. Detailed pH data are given in Appendix A-9.

FIG. 11 COMPARISON OF NH3–N

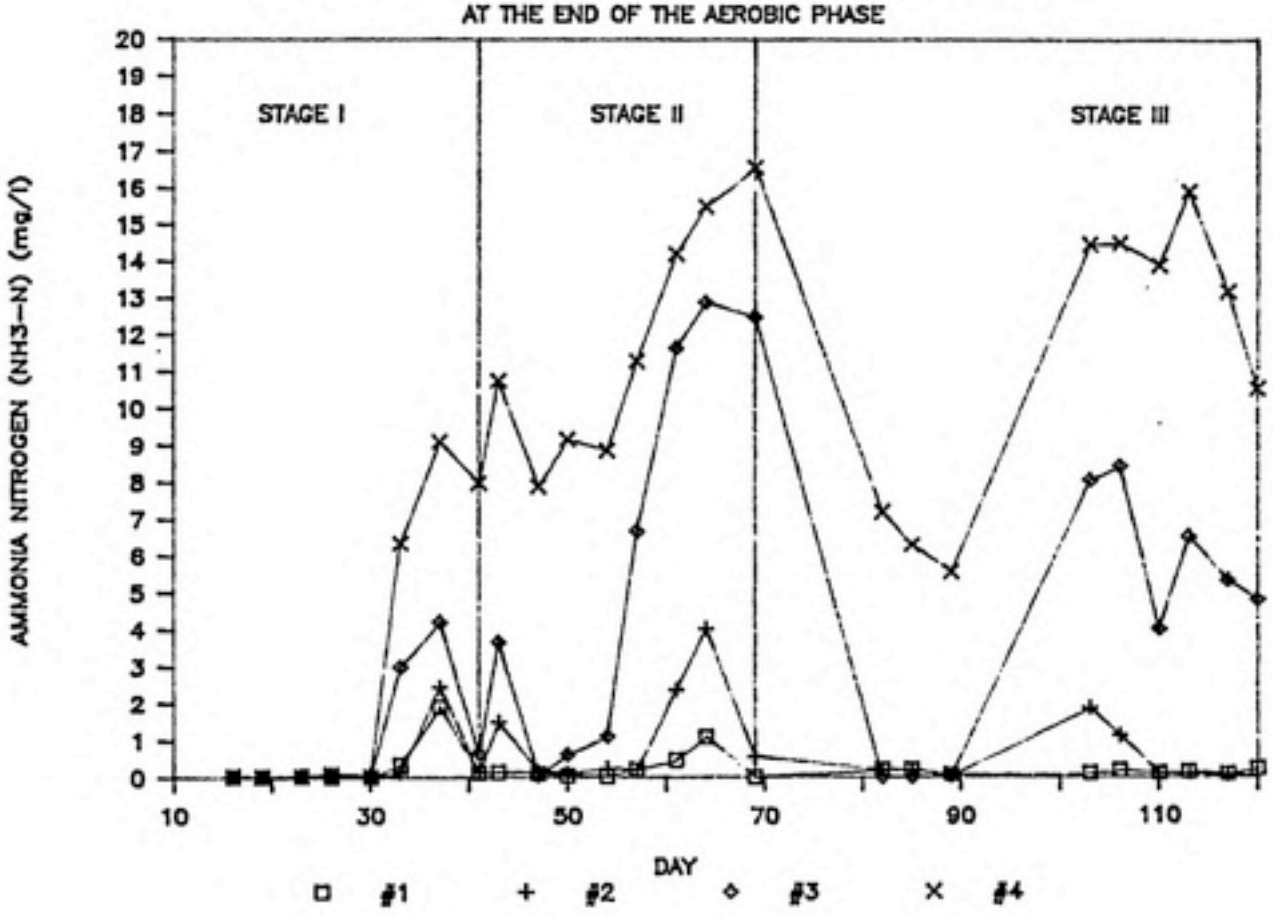


FIG.12 COMPARISON OF NOx–N

AT THE END OF AEROBIC PHASE

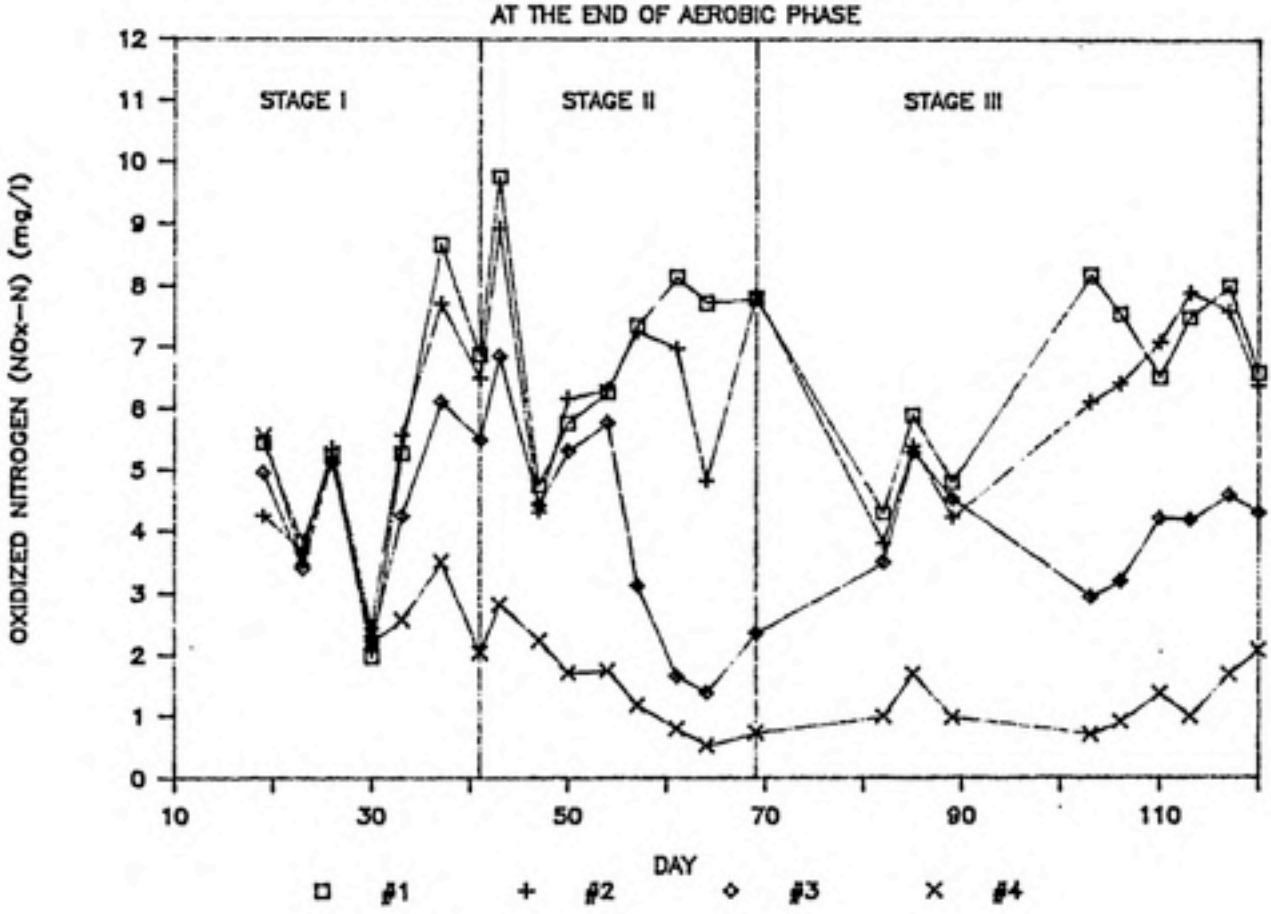


TABLE.15 AVERAGE pH VALUES AT THE END OF ANAEROBIC AND AEROBIC PHASES

STAGE		ANAEROBIC PHASE				AEROBIC PHASE			
		#1	#2	#3	#4	#1	#2	#3	#4
I	AVG	7.1	7.1	7.1	7.0	7.2	7.3	7.3	7.2
	STD	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1
II	AVG	7.0	7.0	7.0	6.9	7.0	7.0	7.3	7.3
	STD	0.1	0.1	~0.0	0.1	0.1	0.1	~0.0	0.1
III	AVG	7.0	6.9	6.9	6.9	7.3	7.2	7.3	7.3
	STD	~0.0	0.1	~0.0	0.1	0.1	0.1	0.1	0.1

Gossett et al. (1978) have observed that alum sludge decreases the biodegradability of organic nitrogen compounds in anaerobic digestion. They speculate that in the flocs the added chemical may form a barrier to the enzymatic hydrolysis of complex materials - a sort of "cage" effect. Perhaps this effect could cause diminished nitrification.

Another possibility is that since alum is a good coagulant, the addition of alum may increase the floc density, which has been shown in the SVIs of alum units in Table 6, causing the interior of the flocs to become anaerobic. The interior anaerobic condition might occur even when the oxygen concentration in bulk liquid is maintained at high level. Since the number of nitrifiers is much smaller than heterotrophic organisms, the nitrifiers will be more sensitive to this interior anaerobic effect. As more alum is added, the possibility of creating the interior anaerobic condition increases. Since phosphorus-accumulating organisms could live well under the aerobic/anaerobic conditions, the interior anaerobic effect may not deteriorate performance of BPR while deteriorating nitrification. More studies need to be done to investigate the inhibitory effects on nitrification by the additions of alum.

CONCLUSIONS

From the results of this experiment, it can be concluded that:

(1) The additions of alum decreased the levels of SVI, MLSS, and MLVSS.

(2) The additions of alum produced higher SS in effluents without increasing BOD5 concentrations.

(3) Acetate plays an important role on the mechanisms of BPR. The more acetate was added (15-40 mg/l C), the better BPR was observed in all units.

(4) No adverse effect on BPR was observed in reactor #2, which received 26 mg/l of alum.The additions of alum in reactors#3 and #4, which received 52 and 104 mg/l of alum, respectively, seem to have no obvious adverse effect on BPR. Theaddition of acetate has greater effect on BPR thanalum dose.

(5) Diminished nitrification was observed in reactors #3 and #4, which showed the poorest nitrification. The additions of alum may not be feasible when both phosphorus removal and nitrification are required.

FUTURE RESEARCH

From the conclusions of this study,there are several areas of research that need to be conducted to investigate the feasibility of combined chemical-BPR activated sludge processes.

(1) Microbiological examinations need to be conducted to further identify the inhibitory effect of alum additions on nitrifiers and heterotrophic organisms.

(2) The effects of acetate, MCRT, and other operation conditions on BPR processes need to be investigated for the optimal BPR operation.

(3) The effects of adding alum with the dosages of based on the treated effluent of BPR instead of constant dosage need to be investigated and compared with this study to evaluate the feasibility of adding alum for the combined treatment.

(4) The effects of the additions of other chemicals, iron salts or lime, on BPR processes need to be investigated to compared with the effects by alum additions.

References

Arora, M. L., Barth, E. F., and Umphres, M. B., "Technology Evaluation of Sequencing Batch Reactors", Journal of the Water Pollution Control Federation, Vol. 57, No. 8, pp. 867-875 (Aug. 1985).

American Public Health Association, American Water Works Association, and Water Pollution Control Federation, "Standard Methods for the Examination of Water and Wastewater," (1985).

Arvin, E., "Observations Supporting Phosphate Removal by Biologically Mediated Chemical Precipitation, "Water Science and Technology, Vol. 15, No. 3-4, pp. 43-63 (1983).

Barnard, J. L., "Background to Biological Phosphorus Removal" Water Science and Technology, Vol. 15, No. 3-4, pp. 1-14 (1983).

Barth, F. E., and Ettinger, M. B., "Mineral Controlled Phosphorus Removal in the Activated Sludge Process," Journal of the Water Pollution Control Federation, Vol. 39, No. 8, pp. 1362-1373 (Sep. 1967).

Barth, F. E., and Stensel, D., "International Nutrient Control Technology for Municipal Effluents," Journal of the Water Pollution Control Federation, Vol. 53, No. 12, pp. 1691-1701 (Dec. 1981).

Brodisch, K. E. U., and Joyner, S. J., "The Role of Micro-organisms Other Than Acinetobacter in Biological Phosphate Removal in Activated Sludge Process," Water Science and Technology, Vol. 15, NO. 3-4, pp. 117-125 (1983).

Buchan, L., "Possible Biological Mechanism of Phosphorus Removal," Water Science and Technology, Vol. 15, No. 3-4,pp. 87-104 (1983).

Chiesa, S. C., and Bordacs, K., "Optimization of Biological Phosphorus Removal in Sequencing Batch Reactors Using Intermittent Carbon Supplementation," Paper Presented at the 59th Annual Conference of the Water Pollution Control Federation, Los Angeles, California (Oct. 1986).

Finger, R. E., "Solids Control in Activated Sludge Plants With Alum, "Journal of the Water Pollution Control Federation, Vol. 45, No. 8, pp. 1645-1662 (Aug. 1973).

Florentz, M., Granger, P., and Hartemann, P., "Use of ^{31}P Nuclear Magnetic Resonance Spectroscopy and Electron Microscopy to Study Phosphorus Metabolism of Micro-organisms from Wastewaters," Applied and Environmental Microbiology, Vol. 47, No. 3, pp. 519-525 (Mar. 1984).

Florentz, M., and Hartemann, P., "Screening for Phosphate Accumulating Bacteria Isolated from Activated Sludge, "Environmental Technology Letters, Vol. 5, pp. 457-463 (1984).

Fuhs, C. W., and Chen, M., "Microbiological Basis of Phosphorus Removal in the Activated Sludge Process for the Treatment of Wastewaters, "Microbiological Ecology, Vol.2, pp.119-138 (1975).

Fukase, T., Shibata, M., and Miyaji, Y., "The Role of an Anaerobic Stage on Biological Phosphorus Removal," Water Science an Technology, Vol. 17, pp. 69-80 (1984).

Gerber, A., Mostert, E. S., Winter, C. T., and Villiers, R.H., "The Effect of Acetate and Other Short-Chain Carbon Compounds on the Kinetics of Biological Nutrient Removal," Water SA, Vol. 12, No.1, pp. 7-12 (Jan. 1986).

Gerber, A., and Winter, C. T., "The Influence of Extended Anaerobic Retention Time on the Performance of Phoredox Nutrient Removal Plants," Water Science and Technology, Vol. 17, pp. 81-92 (1984).

Gossett, J. M., McCarty, P. L., Wilson, J. C., and Evans, D. S., "Anaerobic Digestion of Sludge from Chemical Treatment," Journal of Water Pollution Control Federation, Vol. 50, No. 3, pp. 533-542 (Mar. 1978).

Gray, A. C., Gerber, H. B., and Paul, P. E., "Activated Sludge Process With Alum Addition and Heat Treatment," Journal of the Water Pollution Control Federation, Vol. 48, No. 1, pp. 163-178 (Jan. 1976).

Irvine, R.L., "Sequencing Batch Biological Reactors - An Overview, "Journal of the Water Pollution Control Federation, Vol.51, No. 2, pp. 235-243 (Feb. 1979).

Irvine, R. L., Ketchum, L. H., Arora, M. L., and Barth, E. F., "An Organic Loading Study of Full-Scale Sequencing Batch Reactors,"Journal of the Water Pollution Control Federation, Vol. 59, No. 8, pp. 847-853 (Aug. 1985).

Ketchum, L. H., Irvine, R. L., Breyfogle, R. E., and Manning, J. F., "A Comparison of Biological and Chemical Phosphorus Removals in Continuous and Sequencing Batch Reactors," Journal of the Water Pollution Control Federation, Vol. 59, No.1, pp. 13-18 (Jan. 1987).

Lan, J. C., Benefield, L., and Randall, C. W., "Phosphorus Removal in the Activated Sludge Process,"Water Research, Vol. 17, No. 9, pp. 1193-1200 (1983).

Long, P. A., and Nesbitt, J. B., "Removal of Soluble Phosphorus in an Activated Sludge Plant," Journal of the Water Pollution Control Federation, Vol. 47, No. 1, pp. 170-184 (Jan. 1975).

Lotter, L. H., "The Role of Bacterial Phosphate Metabolism in Enhanced Phosphorus Removal from the Activated Sludge Process," Newsletter of the Study Group on Phosphate Removal in Biological Sewage Treatment Processes, Vol. 2, No. 2 (Feb. 1985).

Mandt, M. G., "The Innovative Technology of Sequencing Batch Reactors," Pollution Engineering, pp. 26-28 (July 1985)

Manning, J. F., and Irvine, R. L., "The Biological Removal of Phosphorus in a Sequencing Batch Reactor", Journal of the Water Pollution Control Federation, Vol. 57,No. 1, pp. 87-94 (Jan. 1985).

Marais, G. V. R., Loewnthal, R. E., and Siebritz, I. P., "Observations Supporting Phosphate Removal by Biological Excess Uptake - A Review," Water Science and Technology, Vol. 15, No. 3-4, pp. 15-42 (1983).

Miyamoto-Mills, J., Larson, J., Jenkins, D., and Owen, W., "Design and Operation of a Pilot-Scale Biological Phosphorus Removal Plant at the Central Contra Costa Sanitary District," Water Science and Technology, Vol. 15, No. 3-4, pp. 153-180 (1983).

Nicholls, H. A.,and Osborn, D. W., "Bacterial Stress: Prerequisite for Biological Removal of Phosphorus," Journal of the Water Pollution Control Federation, Vol.51, No. 3, pp. 557-569 (Mar. 1979).

Potgieter, D. J. J., and Evans, B. W., "Biochemical Changes Associated With Luxury Phosphate Uptake in a Modified Phoredox Activated Sludge System," Water Scienceand Technology, Vol. 15, No. 3-4, pp. 105-115 (1983).

Riding, J. T., Elliott, W. R., and Sherrard, J. H.,"Activated Sludge Phosphorus Removal Mechanisms," Journal of the Water Pollution Control Federation,Vol. 51, No. 5, pp. 1040-1051 (May 1979).

Tetreault, M. J., Benedict, A. H., Kaempfer, C., and Barth, E. F., "Biological Phosphorus Removal: A Technology Evaluation," Journal of the Water Pollution Control Federation, Vol. 58, No. 8, pp. 823-837 (Aug. 1986).

U. S. Environmental Protection Agency, "Process Design Manual for Phosphorus Removal," EPA 625/1-76-001a (Apr. 1976).

U. S. Environmental Protection Agency, "Methods for Chemical Analysis of Water and Wastes," EPA 600/4-79-020 (Mar. 1979).

Unz, R. F., and Davis, J. A., "Microbiology of Combined Chemical-Biological Treatment," Journal of the Water Pollution Control Federation, Vol. 47, No. 1, pp. 185-194 (Jan. 1975).

Walsh, T. K., Behrman, B. W., Weil, G. W., and Jones, E. R.,"A Review of Biological Phosphorus Removal Technology, "Paper Presented at the 56th Annual Conference of the Water Pollution Control Federation (Oct. 1983).

APPENDIX

A-1. PERFORMANCE TESTING STAGE DATA

		AMMONIA NITROGEN (NH3-N) (mg/l)								OXIDIZED NITROGEN (NOx-N) (mg/l)							
		(ANA.)				(AER.)				(ANA.)				(AER.)			
DAY	DATE	#1	#2	#3	#4	#1	#2	#3	#4	#1	#2	#3	#4	#1	#2	#3	#4
1	DEC. 4	7.9	7.7	7.6	7.9	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	7.1	7.3	7.3	7.0
2	5	8.0	8.3	6.5	8.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.8	7.6	7.6	7.7
3	6	7.2	7.2	7.2	7.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.7	7.7	7.5	7.1
4	7	6.3	6.8	6.8	6.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.3	6.3	6.9	5.5
5	8	7.0	7.8	8.0	8.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.5	7.7	7.8	7.8
6	9	7.7	7.9	8.1	8.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.4	7.4	7.6	7.6
	AVG	7.4	7.6	7.7	7.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.5	7.3	7.4	7.1
	STD	0.6	0.5	0.6	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.5	0.3	0.8

		ORTHO-PHOSPHATE (PO4-P) (mg/l)								pH							
		(ANA.)				(AER.)				(ANA.)				(AER.)			
DAY	DATE	#1	#2	#3	#4	#1	#2	#3	#4	#1	#2	#3	#4	#1	#2	#3	#4
1	DEC. 4	24	19	22	24	0.1	0.1	0.0	0.0								
2	5	26	23	26	27	0.0	0.0	0.0	0.0	7.0	7.1	7.1	7.1	7.2	7.3	7.3	7.4
3	6	22	20	22	25	0.0	0.0	0.0	0.0	6.9	7.0	7.1	7.1	7.1	7.1	7.2	7.1
4	7	29	23	27	28	0.0	0.0	0.0	0.0	7.1	7.1	7.2	7.0	7.2	7.2	7.2	7.2
5	8	29	23	31	28	0.0	0.0	0.0	0.0	7.1	7.0	7.1	7.0	7.4	7.2	7.3	7.2
6	9	32	31	34	33	0.0	0.0	0.0	0.0	7.0	6.9	7.0	7.0	7.2	7.2	7.3	7.2
	AVG	27	23	27	27	0.0	0.0	0.0	0.0	7.0	7.0	7.1	7.0	7.2	7.2	7.2	7.2
	STD	3	4	4	3	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.0	0.1

		SUSPENDED SOLIDS (MLSS) (mg/l)				SLUDGE VOLUME INDEX (SVI) (ml/g)			
DAY	DATE	#1	#2	#3	#4	#1	#2	#3	#4
1	Dec. 4	1507	1288	1385	1421	345	443	318	443
5	8	1847	1647	1463	1774	347	455	437	411
	AVG	1677	1468	1424	1598	346	449	378	427
	STD	170	180	39	177	1	6	60	16

A-2. DATA FOR TESTING PARTIALLY FAVORABLE BPR CONDITION

DAY	DATE	OPERATION
70	FEB.11	ADD SODIUM ACETATE OF 20 mg/l CARBON TO REACTOR #1
72	FEB.13	DILUTE THE ACETATE CONCENTRATION TO 10 mg/l CARBON
77	FEB.18	CHANGE THE ACETATE CONCENTRATION TO 15 mg/l CARBON
81	FEB.22	ADD SODIUM ACETATE (15 mg/l CARBON) TO ALL UNITS

PO4-P DATA OF REACTOR #1 AT THE END OF AEROBIC PHASE

	METHOD	
DAY	HACH	ANALYZER
71	0.0	0.1
76	1.0	
77	0.5	
78		1.0

ALL VALUES ARE EXPRESSED IN mg/l

A-3. PRIMARY EFFLUENT - SYSTEM INFLUENT CHARACTERISTICS

DAY	DATE	pH	NH3-N	NOx-N	PO4-P	TP	TKN	BOD5	SS
8	DEC.11	7.3	16.5	0.1	3.1	5.4	24	86	31
13	16	7.3	17.6	0.0	1.9				
16	19	7.3	14.2		4.0	7.4	29	122	72
19	22	7.2	19.6	0.0	4.0				
23	26	7.2	9.7	0.2	1.7	3.4	15	96	41
26	29	7.1	16.1	0.1	3.3				
30	JAN. 2	7.2	7.7	0.0	1.4	3.1	16	105	81
33	5	7.3	19.3	0.1					95
37	9	7.4	23.3	0.0	4.6	7.3	36	138	80
41	13	7.3	22.6	0.0	4.1				
43	15	7.3	22.5	0.0	3.9	4.9	35	113	68
47	19	7.1	12.9	0.5	1.5				
50	22	7.0	10.1	0.4	1.4	3.4	19	46	75
54	26	7.3	14.6	0.1					64
57	29	7.3	15.9	0.2	2.6		31	90	71
61	FEB. 2	7.5	21.2	0.1	3.6	7.4	34	116	63
64	5	7.4		0.1	2.8	5.5	32	100	108
69	10	7.2	22.1	0.0	2.8				103
71	12	7.1	20.1	0.0	2.5		35	124	156
76	17	7.4	20.7	0.1	4.0		29		72
78	19	7.3	16.2	0.3	2.9			115	
82	23	7.2	10.6	0.7	2.7				76
85	26	7.0	14.3	0.6	3.4	6.1	25	166	68
89	MAR. 2	7.1	11.6	0.3	2.4				
99	12	7.0	7.1	0.5	5.2	5.5	27		146
103	16	7.2	20.9	0.0	3.6				
106	19	7.1	19.2	0.2	3.1	4.4	25	120	79
110	23	7.1	16.6	0.1	2.8				
113	26	7.1	19.9	0.1	3.1	6.4	35	138	85
117	30	7.1	21.4	0.0	3.8				
120	APR. 2	7.1	18.5	0.0	3.2	4.9	25	139	60
	AVG	7.2	16.8	0.2	3.1	5.4	28	113	81
	STD	0.1	4.8	0.2	1.0	1.5	7	27	30
	MAX	7.5	23.3	0.7	5.2	7.4	36	166	156
	MIN	7.0	7.1	0.0	1.4	3.1	15	46	31

ALL VALUES EXCEPT pH ARE EXPRESSED IN mg/l

A-4. MIXED LIQUOR SOLIDS CHARACTERISTICS

			MLSS (mg/l)				MLVSS (mg/l)				MLVSS (%)				SVI (ml/g)			
Stage	Day	Date	#1	#2	#3	#4	#1	#2	#3	#4	#1	#2	#3	#4	#1	#2	#3	#4
	23	DEC.26	1624	1494	1491	1664	1388	1283	1242	1264	85	86	83	76	166	127	101	78
I	28	31	1653	1349	1241	1420	1389	1111	1069	1098	84	82	86	77	151	111	89	70
	33	JAN. 5	1408	1485	1119	1114	1239	1218	985	925	88	82	88	83	156	101	80	81
	37	9	1464	1267	1369	1529	1221	1066	1122	1180	83	84	82	77	164	118	88	85
		AVG	1537	1399	1305	1432	1309	1169	1104	1117	85	84	85	78	159	114	90	79
		STD	104	95	139	203	79	86	93	125	2	2	2	3	6	10	8	6
	43	JAN.15	1427	1237	1191	1244	1256	1067	1012	1010	88	86	85	81	175	121	76	96
	50	22	1066	916	883	808	909	781	719	626	85	85	81	77	169	120	68	74
	54	26	1055	824	628	803	868	660	516	571	82	80	82	71	190	133	127	100
II	57	29	1395	977	806	1472	1149	761	627	1019	82	78	78	69	136	113	62	54
	61	FEB. 2	1188	1400	575	842	1038	1105	505	638	87	79	88	76	143	71	52	59
	64	5	918	775	610	1026	680	598	507	708	74	77	83	69	185	103	82	49
	69	10	1365	968	638	850	1073	791	532	682	79	82	83	80	139	114	78	59
		AVG	1202	1014	762	1006	996	823	631	751	82	81	83	75	162	111	78	70
		STD	183	209	204	241	178	178	172	172	4	3	3	5	21	18	22	19
	82	FEB.23	2003	1705	1455	1043	1487	1208	1050	707	74	71	72	68	275	88	69	58
	85	26	1617	1399	1425	1274	1216	1039	982	838	75	74	69	66	204	86	70	47
III	99	MAR.12	1870	1039	1101	1129	1322	758	756	745	71	73	69	66	155	67	45	44
	106	19	1742	1066	758	1222	1226	831	531	869	70	78	70	71	132	75	66	49
	113	26	1905	1274	1026	1525	1422	926	758	965	75	73	74	63	163	86	49	66
	120	APR. 2	1902	950	717	1546	1407	752	551	1027	74	79	77	66	205	84	42	71
		AVG	1840	1239	1080	1290	1347	919	771	859	73	75	72	67	189	81	57	56
		STD	126	257	288	188	101	163	195	113	2	3	3	2	46	8	12	10

A-5. EFFLUENT CHARACTERISTICS

STAGE	DAY	DATE	TP (mg/l)				TKN (mg/l)				BOD5 (mg/l)				SS (mg/l)			
			#1	#2	#3	#4	#1	#2	#3	#4	#1	#2	#3	#4	#1	#2	#3	#4
	16	DEC.19									1	3	3	1				
	23	26									1	2	2	0				
	30	JAN. 2	0.2	0.4	0.3	0.1	1.1	1.6	1.8	1.0	2	3	3	1	5	8	17	10
I	33	5	0.5	0.6	0.4	0.3	2.1	2.6	4.5	8.2								
	37	9	0.7	0.4	0.4	0.5	5.2	5.1	7.2	12.0	2	2	3	3	9	9	21	21
	41	13	0.5	0.7	0.5	0.5	2.1	2.6	2.5	11.7								
		AVG	0.4	0.5	0.4	0.3	2.6	3.0	4.0	8.2	2	3	2	1	7	9	19	16
		STD	0.2	0.1	0.1	0.1	1.6	1.3	2.1	4.4	1	0	0	1	2	1	2	6
	43	JAN.15									2	2	2	2	6	5	17	19
	47	19	2.2	0.5	0.9	0.2	1.6	1.9	7.7	8.2								
	50	22	1.0	1.5	0.5	0.2	2.0	2.6	1.8	11.0	1	2	2	1	12	13	17	19
II	54	26	3.1	1.5	1.1	0.4	1.3	1.0	2.7	10.1	4	3	3	2				
	61	FEB. 2	2.6	1.5	1.3	0.7	1.5	3.4	15.2	17.5	4	5	5	4				
	64	5	1.6	1.0	1.7	1.3	2.1	3.4	14.2	18.0	3	5	3	3	9	14	38	28
	69	10	2.2	0.6	1.4	0.9	1.0	2.0	16.2	19.0					7	9	26	22
		AVG	2.1	1.1	1.2	0.6	1.6	2.4	9.6	14.0	3	3	3	2	9	10	25	22
		STD	0.7	0.4	0.4	0.4	0.4	0.8	5.9	4.3	1	1	1	1	2	4	9	4
	85	FEB.26	2.8	0.5	0.4	0.7	2.0	1.5	1.6	8.1	3	3	3		4	6	12	14
	89	MAR. 2	1.9	0.4	0.5	0.3	1.4	1.2	1.8	7.6								
	103	16	0.3	0.6	0.7	0.6	1.6	3.5	8.7	16.2								
	106	19	0.1	0.3	0.6	0.6	1.3	2.2	10.3	12.7	3	5	4	5	10	16	26	22
III	110	23	4.1	0.5	0.7	0.6	1.4	2.0	6.7	15.9								
	113	26	0.2	0.6	1.6	0.5	1.5	2.2	10.2	18.0	3	4	4	3	6	13	29	16
	117	30	1.5	0.7	1.2	0.3	1.0	1.8	6.8	16.8								
	120	APR. 2	0.8	0.7	1.5	0.3	1.5	1.6	6.8	13.2	2	4	4	2	4	13	28	17
		AVG	1.4	0.5	0.9	0.5	1.5	2.0	6.6	13.5	3	4	4	3	6	12	24	17
		STD	1.3	0.1	0.4	0.1	0.3	0.7	3.2	3.7	1	1	0	1	2	4	7	3

A-6. ORTHOPHOSPHATE (PO4-P) DATA - (mg/l)

				ANAEROBIC PHASE				AEROBIC PHASE				EFFLUENT			
STAGE	DAY	DATE	INF.	#1	#2	#3	#4	#1	#2	#3	#4	#1	#2	#3	#4
	16	DEC.19	4.0	15.3	12.2	10.6	9.0	0.0	0.0	0.0	0.0				
	19	22	4.0	20.7	14.7	15.9	10.4	0.0	0.0	0.0	0.0				
	23	26	1.7	10.1	9.3	8.3	3.9	0.2	0.2	0.2	0.2				
	26	29	3.3	4.4	3.2	3.0	2.2	0.2	0.2	0.2	0.2				
I	30	JAN. 2	1.4	13.7	9.5	9.3	5.0	0.0	0.0	0.0	0.0				
	33	5		14.6	12.1	9.4	7.9	0.0	0.0	0.0	0.0				
	37	9	4.6	8.9	6.0	14.4	10.3	0.0	0.0	0.0	0.0				
	41	13	4.1	20.1	13.3	12.9	8.6	0.0	0.0	0.0	0.0				
		AVG	3.3	13.4	10.1	10.5	7.1	0.1	0.1	0.1	0.1				
		STD	1.2	5.2	3.7	3.8	2.9	0.1	0.1	0.1	0.1				
	43	JAN.15	3.9	5.8	4.9	3.2	2.2	1.5	0.2	0.0	0.0				
	47	19	1.5	2.4	0.8	0.8	0.4	2.4	0.8	0.4	0.0	2.3	0.6	0.1	0.0
	50	22	1.4	2.5	2.3	1.6	1.4	2.1	1.1	0.3	0.1	2.5	1.2	0.1	0.0
II	54	26						2.7	1.4	0.5	0.0	2.6	1.1	0.0	0.0
	57	29	2.6	3.9	3.5	1.6	0.9	2.5	1.8	0.6	0.0				
	61	FEB. 2	3.6	6.5	6.2	4.9	4.3	1.9	1.3	0.6	0.1				
	64	5	2.8	3.1	2.5	2.8	2.8	1.2	0.4	0.2	0.1	1.3	0.2	0.1	0.0
	69	10	2.8	4.7	4.3	4.2	2.6	2.0	1.0	0.9	0.1	2.3	0.9	0.4	0.0
		AVG	2.7	4.1	3.5	2.7	2.1	2.0	1.0	0.4	0.0	2.2	0.8	0.1	0.0
		STD	0.9	1.5	1.7	1.4	1.2	0.5	0.5	0.2	0.0	0.5	0.3	0.1	0.0
	82	FEB.23	2.7	8.2	6.6	5.3	2.5	3.9	0.2	0.0	0.0				
	85	26	3.4	7.2	5.8	4.5	0.3	2.9	0.1	0.0	0.0	3.9	0.1	0.0	0.0
	89	MAR. 2	2.4	3.8	4.4	2.2	0.1	1.5	0.1	0.0	0.0	1.6	0.1	0.0	0.0
	103	16	3.6	13.2	10.8	9.4	6.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
III	106	19	3.1	14.0	12.3	10.7	7.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	110	23	2.8	15.0	9.5	8.2	8.4	3.2	0.0	0.0	0.0	3.1	0.0	0.1	0.0
	113	26	3.1	16.5	12.4	11.3	8.8	0.2	0.0	0.0	0.0	0.3	0.0	0.0	0.0
	117	30	3.8	17.2	14.8	9.7	7.3	1.9	0.7	0.0	0.0	2.2	0.6	0.0	0.0
	120	APR. 2	3.2	18.9	15.3	13.8	11.2	0.4	0.0	0.0	0.0	0.3	0.0	0.0	0.0
		AVG	3.1	12.7	10.2	8.3	5.8	1.6	0.1	0.0	0.0	1.4	0.1	0.0	0.0
		STD	0.4	4.8	3.7	3.5	3.7	1.4	0.2	0.0	0.0	1.4	0.2	0.0	0.0

A-7. AMMONIA NITROGEN (NH_3-N) DATA - (mg/l)

				ANAEROBIC PHASE				AEROBIC PHASE				EFFLUENT			
STAGE	DAY	DATE	INF.	#1	#2	#3	#4	#1	#2	#3	#4	#1	#2	#3	#4
	16	DEC.19	14.2	4.1	4.6	3.4	5.8	0.0	0.0	0.0	0.0				
	19	22	19.6	7.0	5.7	6.6	6.8	0.0	0.0	0.0	0.0				
	23	26	9.7	3.7	4.2	3.6	4.0	0.0	0.0	0.0	0.0				
	26	29	16.1	5.6	5.7	5.8	5.7	0.0	0.1	0.0	0.1				
I	30	JAN. 2	7.7	2.7	2.1	2.3	2.7	0.0	0.0	0.1	0.0				
	33	5	19.3	8.2	11.8	7.7	12.3	0.3	0.1	3.0	6.3				
	37	9	23.3	11.4	11.0	12.1	14.9	1.9	2.5	4.2	9.1				
	41	13	22.6	8.4	7.9	8.3	13.9	0.1	0.1	0.7	8.0				
		AVG	16.6	6.4	6.6	6.2	8.3	0.3	0.4	1.0	2.9				
		STD	5.4	2.7	3.2	3.0	4.4	0.6	0.8	1.5	3.8				
	43	JAN.15	22.5	9.2	10.3	11.2	16.0	0.1	1.5	3.7	10.7				
	47	19	12.9	4.9	4.0	5.0	10.9	0.1	0.2	0.0	7.9	0.1	0.4	0.2	8.3
	50	22	10.1	4.8	5.2	5.7	12.2	0.0	0.1	0.6	9.2	0.0	0.2	0.6	9.8
	54	26	14.6					0.0	0.3	1.1	8.9	0.3	0.3	1.1	7.9
II	57	29	15.9	6.5	6.2	9.5	12.9	0.2	0.2	6.7	11.3	0.3	0.3	6.4	11.4
	61	FEB. 2	21.2	8.2	8.9	14.1	16.0	0.5	2.4	11.6	14.2	0.2	1.9	11.1	13.6
	64	5		8.0	8.5	14.4	16.4	1.1	4.0	12.9	15.5	0.1	1.3	11.7	14.7
	69	10	22.1	8.1	8.3	14.9	25.5	0.0	0.6	12.5	16.6	0.1	0.0	9.8	16.2
		AVG	17.0	7.1	7.3	10.7	15.7	0.3	1.1	6.1	11.8	0.2	0.6	5.8	11.7
		STD	4.6	1.6	2.1	3.8	4.5	0.3	1.3	5.2	3.0	0.1	0.6	4.8	3.0
	82	FEB.23	10.6	3.8	3.4	3.3	8.8	0.2	0.2	0.0	7.2				
	85	26	14.3	4.9	4.4	4.4	6.3	0.2	0.2	0.0	6.3	0.2	0.2	0.0	6.1
	89	MAR. 2	11.6	3.2	3.8	3.5	6.0	0.1	0.0	0.0	5.6	0.1	0.0	0.0	5.7
	103	16	20.9	7.9	8.4	11.9	16.1	0.1	1.9	8.1	14.5	0.1	0.3	2.3	5.1
III	106	19	19.2	7.7	8.7	12.8	17.0	0.2	1.1	8.5	14.5	0.0	0.4	7.9	14.2
	110	23	16.6	5.9	6.7	8.7	14.3	0.1	0.1	4.0	13.9	0.2	0.1	4.5	11.4
	113	26	19.9	7.0	7.0	11.8	17.5	0.1	0.1	6.5	15.9	0.0	0.2	6.1	15.9
	117	30	21.4	7.2	8.2	10.9	15.3	0.1	0.1	5.4	13.2	0.1	0.1	5.0	12.6
	120	APR. 2	18.5	6.8	7.0	10.5	14.1	0.2	0.1	4.8	10.6	0.2	0.0	4.3	10.5
		AVG	17.0	6.0	6.4	8.6	12.8	0.1	0.4	4.1	11.3	0.1	0.2	3.8	10.2
		STD	3.8	1.6	1.9	3.6	4.3	0.1	0.6	3.2	3.8	0.1	0.1	2.6	3.9

A-8. OXIDIZED NITROGEN (NOx-N) DATA - (mg/l)

				ANAEROBIC PHASE				AEROBIC PHASE				EFFLUENT			
STAGE	DAY	DATE	INF.	#1	#2	#3	#4	#1	#2	#3	#4	#1	#2	#3	#4
	19	DEC.22	0.0	0.0	0.0	0.0	0.0	5.5	4.3	5.0	5.6				
	23	26	0.2	0.0	0.0	0.0	0.0	3.8	3.7	3.4	3.6				
	26	29	0.1	0.0	0.0	0.0	0.0	5.2	5.4	5.1	5.3				
I	30	JAN. 2	0.0	0.0	0.0	0.0	0.0	2.0	2.4	2.2	2.2				
	33	5	0.1	0.0	0.0	0.0	0.0	5.3	5.6	4.3	2.6				
	37	9	0.0	0.0	0.0	0.0	0.0	8.7	7.7	6.1	3.5				
	41	13	0.0	0.0	0.0	0.0	0.0	6.9	6.5	5.5	2.0				
		AVG	0.1	0.0	0.0	0.0	0.0	5.3	5.1	4.5	3.5				
		STD	0.1	0.0	0.0	0.0	0.0	2.0	1.6	1.2	1.3				
	43	JAN.15	0.0	0.0	0.0	0.0	0.0	9.7	8.9	6.8	2.8				
	47	19	0.5	0.0	0.0	0.0	0.0	4.7	4.3	4.4	2.2	4.6	4.0	4.5	2.4
	50	22	0.4	0.1	0.0	0.0	0.0	5.8	6.2	5.3	1.7	6.0	5.0	5.0	1.6
	54	26	0.1	0.0	0.0	0.0	0.0	6.3	6.3	5.8	1.8	6.0	6.0	5.9	1.7
II	57	29	0.2	0.0	0.0	0.0	0.0	7.3	7.3	3.1	1.2	6.5	6.8	3.5	1.3
	61	FEB. 2	0.1	0.0	0.0	0.0	0.0	8.1	7.0	1.7	0.8	8.2	6.2	2.2	0.8
	64	5	0.1	0.0	0.0	0.0	0.0	7.7	4.8	1.4	0.5	8.4	7.3	2.1	0.7
	69	10	0.0	0.0	0.0	0.0	0.0	7.8	7.9	2.4	0.7	7.0	6.8	2.0	1.1
		AVG	0.2	0.0	0.0	0.0	0.0	7.2	6.6	3.9	1.5	6.7	6.0	3.6	1.4
		STD	0.2	0.0	0.0	0.0	0.0	1.5	1.4	1.9	0.8	1.2	1.1	1.4	0.5
	82	FEB.23	0.7	0.0	0.0	0.0	0.0	4.3	3.8	3.5	1.0				
	85	26	0.6	0.0	0.0	0.0	0.0	5.9	5.4	5.3	1.7	5.3	5.3	5.3	1.8
	89	MAR. 2	0.3	0.0	0.0	0.0	0.0	4.8	4.2	4.5	1.0	4.9	4.2	4.5	1.1
	103	16	0.0	0.0	0.0	0.0	0.0	8.2	6.1	3.0	0.7	4.2	11.0	5.5	0.3
III	106	19	0.2	0.0	0.1	0.1	0.0	7.6	6.4	3.2	0.9	7.7	7.7	4.1	1.1
	110	23	0.1	0.0	0.0	0.0	0.0	6.5	7.1	4.2	1.4	7.2	5.3	6.3	1.3
	113	26	0.1	0.0	0.0	0.0	0.0	7.5	7.9	4.2	1.0	7.6	7.4	5.0	1.2
	117	30	0.0	0.0	0.0	0.0	0.0	8.0	7.6	4.6	1.7	8.0	7.5	4.9	1.9
	120	APR. 2	0.0	0.0	0.0	0.0	0.0	6.6	6.4	4.3	2.1	6.6	6.4	4.7	2.4
		AVG	0.2	0.0	0.0	0.0	0.0	6.6	6.1	4.1	1.3	6.4	6.8	5.0	1.4
		STD	0.2	0.0	0.0	0.0	0.0	1.3	1.3	0.7	0.4	1.4	1.9	0.6	0.6

A-9. pH DATA

				ANAEROBIC PHASE				AEROBIC PHASE				EFFLUENT			
STAGE	DAY	DATE	INF.	#1	#2	#3	#4	#1	#2	#3	#4	#1	#2	#3	#4
	16	DEC.19	7.3	7.2	7.2	7.2	7.0	7.3	7.3	7.4	7.2	7.6	7.3	7.3	7.0
	19	22	7.2	6.9	7.1	7.0	7.0	6.9	7.1	7.1	7.0	7.6	7.4	7.3	6.8
	23	26	7.2	7.2	7.1	7.4	7.0	7.5	7.5	7.5	7.4	7.7	7.6	7.5	6.9
I	26	29	7.1	7.2	7.0	7.0	6.8	7.5	7.4	7.4	7.2	7.5	7.3	7.2	6.7
	30	JAN. 2	7.2	7.2	7.1	7.1	7.0	7.4	7.5	7.4	7.3	7.7	7.7	7.4	7.0
	33	5	7.3	7.2	7.2	7.2	7.0	7.2	7.2	7.2	7.2	7.5	7.3	7.1	6.9
	37	9	7.4	7.0	7.0	7.0	7.0	6.9	6.9	7.1	7.0	7.1	7.0	7.1	6.9
	41	13	7.3	7.1	7.1	7.1	7.0	7.1	7.1	7.2	7.2	7.4	7.3	7.0	7.0
		AVG	7.3	7.1	7.1	7.1	7.0	7.2	7.3	7.3	7.2	7.5	7.4	7.2	6.9
		STD	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.2	0.2	0.1	0.1
	43	JAN.15	7.3	6.8	6.8	6.8	6.8	6.5	6.6	6.7	7.0	7.0	6.8	6.7	6.7
	47	19	7.1	6.7	6.7	6.6	6.5	6.7	6.7	6.7	6.8	7.1	6.9	6.3	6.4
	50	22	7.0	6.9	6.8	6.7	6.7	6.8	6.6	6.5	6.9	7.3	7.2	6.7	6.5
		AVG	7.1	6.8	6.7	6.7	6.6	6.7	6.6	6.6	6.9	7.1	6.9	6.6	6.5
	57	JAN.29	7.3	7.1	7.1	7.0	6.8	7.1	7.1	7.3	7.2	7.3	7.3	7.5	6.9
II	61	FEB. 2	7.5	7.0	7.0	7.0	6.9	6.9	6.9	7.3	7.2	7.3	7.4	7.6	7.1
	64	5	7.4	7.1	7.0	7.0	7.1	6.8	7.0	7.3	7.3	7.2	7.1	7.0	7.1
	69	10	7.1	7.0	6.8	7.0	6.9	7.1	7.0	7.4	7.3	7.4	7.0	7.4	7.1
		AVG	7.3	7.0	7.0	7.0	6.9	7.0	7.0	7.3	7.3	7.3	7.2	7.4	7.0
		STD	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.2	0.2	0.1
	82	FEB.23	7.2	7.0	7.0	6.9	6.9	7.1	7.2	7.1	7.3				
	85	26	7.0	7.0	7.0	6.9	6.7	7.5	7.4	7.4	7.5	7.6	7.5	7.4	7.0
	89	MAR. 2	7.1	7.1	7.0	6.9	6.7	7.4	7.4	7.3	7.4	7.4	7.2	7.0	6.8
	103	16	7.2	7.0	7.0	7.0	6.9	7.3	7.1	7.3	7.4	7.2	7.0	7.0	6.9
III	106	19	7.1	7.0	7.0	7.0	6.9	7.3	7.1	7.3	7.3	7.4	7.1	7.2	7.1
	110	23	7.1	7.0	7.0	7.0	6.9	7.3	7.2	7.3	7.4	7.3	7.2	7.0	7.1
	113	26	7.1	7.0	7.0	7.0	6.9	7.1	7.1	7.2	7.3	7.4	7.3	7.2	7.1
	117	30	7.1	7.0	6.7	7.0	7.0	7.2	7.2	7.2	7.3	7.3	7.2	7.0	6.9
	120	APR. 2	7.1	6.9	6.7	6.9	6.8	7.3	7.2	7.2	7.2				
		AVG	7.1	7.0	6.9	6.9	6.9	7.3	7.2	7.3	7.3	7.4	7.2	7.1	7.0
		STD	0.1	0.0	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

SODIUM BICARBONATE WAS NOT PROVIDED UNTIL DAY 55